BARRIERS TO BIOWEAPONS

THE CHALLENGES OF EXPERTISE AND ORGANIZATION FOR WEAPONS DEVELOPMENT

SONIA BEN OUAGRHAM-GORMLEY

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Barriers to Bioweapons

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Barriers to Bioweapons

The Challenges of Expertise and Organization for Weapons Development

Sonia Ben Ouagrham-Gormley

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Cover photograph: H5N1 virus and 1960s-era photograph of Soviet anti-plague scientists, displayed at the anti-plague institute in Tashkent, Uzbekistan, 2002.

To my loving husband, Dennis

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Preface and Acknowledgments

When the Soviet Union broke up and revealed the enormity and desperate state of its former bioweapons complex, like many researchers and policy analysts then, I was convinced that a state or terrorist group could readily exploit the expertise available at these former facilities and use it to produce a bioweapon. But after spending extensive time in the former Soviet Union, interacting with former bioweapons scientists supported by government or privately funded research, I found that my assessment of the threat began to change. Several themes started to emerge from my discussions with these individuals about their past bioweapons work and their current civilian work. A key observation—the importance of which I came to appreciate only later—is that working with live organisms is not easy. Live agents are capricious, and modifying or controlling their behavior to achieve specific objectives requires special knowledge and skills. Second, it was clear that the economic, political, and social environment in which people worked affected their results. Being an economist and a student of industrialization, particularly in the Soviet context, I was not surprised by this finding. But not until September 11, 2001, and the anthrax letters did I start to link these two themes and examine their role in shaping the threat of bioweapons proliferation.

Although the 2001 events seemed to corroborate the imminence of the bioweapons threat, contemporary assessments seemed to ignore three important questions: What is bioweapons knowledge? How can it be acquired and transferred? What facilitates or impedes bioweapons developments? These questions spurred the start of a research project, conducted in cooperation with Kathleen Vogel at Cornell University, with support from the Carnegie Corporation of New York. The project aimed to produce an oral

history of the American and Soviet bioweapons programs, to better understand what is specific to bioweapons work and what determines the success rate and outcome of a program. Interviews with former bioweaponeers conducted in the United States, Russia, and Kazakhstan between 2008 and 2012 told a story about past bioweapons efforts that requires us to reconsider current threat assessments. Put simply, their testimonies show how difficult, protracted, and expensive bioweapons efforts have been; outcomes rarely achieved what the magnitude of investment might have suggested. This is good news for nonproliferation. The bad news, however, lies in our ignorance of key determinants of bioweapons development that create new opportunities for proliferation. Using this real-world experience, and complementing it with the analysis of archival data and published documents about U.S., Soviet, and smaller state and terrorist programs, this book offers a new analytical framework, which I hope will foster more accurate threat assessments and the development of more robust policies to diminish the threat of bioweapons even further.

I selected the cases analyzed in this book because there is sufficient public information related to organizational, managerial, and other exogenous variables to allow a detailed analysis of their effects on different program contexts. Such data on the Japanese WWII-era biological weapons program are not available, hence the program is not studied in this book. Source data for chapter 6 dealing with the Iraqi, South African, and Aum Shinrikyo programs were derived from published information related to the investigations and trials that followed the discovery of these three covert programs, as well as other analyses. Source information supporting the analysis of the U.S. and Soviet programs is largely based on empirical studies I have conducted over the past dozen years, most notably the aforementioned Carnegie Corporation–supported four-year (2008–2012) oral history research project. The project gathered about fifty interviews of American and Soviet scientific, technical, and administrative personnel. Interviewees were selected to achieve a sufficient representation of various age brackets, time spent working in the program, specific expertise—bacteria or viruses; animal, plant, or human diseases—and position (bench scientist or technician; lab/facility director, safety/testing, or administrative personnel). Several individuals were subject to multiple follow-up interviews, and some also contributed to round-table talks organized at George Mason University, Fairfax, Virginia; Cornell University, Ithaca, New York; and the Woodrow Wilson Center, Washington, D.C., where they answered questions from students, policy experts, and academics.

The selection of interview subjects on the Soviet side was based on connections made during my decade-long experience studying bioweapons proliferation on the ground in the former Soviet Union. I spent two years in Kazakhstan (1999–2001), working as a senior research associate at the

Monterey Institute of International Studies' James Martin Center for Nonproliferation Studies, and traveled from there to visit former bioweapons facilities in Russia, central Asia, and the Caucasus and interview personnel. Supported by the Nuclear Threat Initiative, I spent another four years working with Monterey Institute colleagues analyzing the former Soviet Antiplague System—a network of more than one hundred facilities that worked on public health projects and offensive and defensive bioweapons projects. The connections thus made allowed for candid discussions with cooperative interviewees, who also connected me with current and former employees of other bioweapons facilities. For about two years, I was also involved in the implementation of the Cooperative Threat Reduction (CTR) Program in Russia—a program sponsored by the Department of Defense to reduce the bioweapons proliferation threat in former Soviet states. The CTR experience fostered a greater appreciation of the successes and challenges faced in developing effective nonproliferation policies.

On the U.S. side, the selection of interviewees resulted from a snowball sampling technique. Having begun with former bioweapons scientists with a public profile—such as William C. Patrick, who was often in the news after the events of September 2001—the interview list spread to former colleagues and friends in the bioweapons program still living in Frederick, Maryland, near the cite of the former U.S. bioweapons program. More contacts were made during reunions of the former program's personnel, which take place annually at Fort Detrick in Frederick. Some interviews were conducted during the reunion that I attended in 2008, while others took place after the reunion, with individuals met on site. These interviews were complemented by archival data research, declassified information, and the review of published analyses about the U.S. and Soviet programs.

Although I made all possible efforts to corroborate the data collected from interviews by cross-checking it via interviews with other individuals and published or archival data, there were important limitations that need to be emphasized. The pool of U.S. and Soviet bioweaponeers available for interview was limited for various reasons. On the U.S. side, the population is aging, and it was not possible to meet individuals representing all of the categories previously identified. On the Soviet side, the pool is larger, but we were constrained for security reasons. It has become increasingly difficult for former bioweapons scientists to openly discuss their former work with foreigners even though the interviews concerned the social context in which they worked and not the types of weapons they produced. These limitations, however, should not altogether dismiss the value of data collected from a diminishing number of participants in the world's two largest bioweapons programs. The names of the interviewees have been kept anonymous due to their wishes specified in the informed consent forms, or for security reasons in the case of living former Soviet scientists still working in former bioweapons facilities. The names of interviewees are provided in

only two cases: when the individuals have passed away, or when they made quoted comments during one of the public events discussed previously.

Every author experiences book writing in different ways. Mine has been a journey of discovery and learning, along which many people have helped me. I am grateful to all the former U.S. and Soviet scientists, technicians, and administrative personnel who agreed to be interviewed for this book and provided unique insight and historical documents. I cannot name most of them due to their desire to remain anonymous, but I would like to give special thanks to Sergei Popov, Guennady Lepioshkin, Norman Covert, Manuel Barbeito, and Orley Bourland for agreeing to shed their anonymity in order to discuss their experiences with biodefense students at George Mason University, as well as science and Russian language students at Cornell University. This work would not have been possible without their time and effort. I would also like to express my sincere gratitude to the Carnegie Corporation of New York—especially Patricia Nicholas, whose support and encouragement during the project allowed us to bring it to completion.

I'm grateful to my George Mason University colleagues for their support and encouragement throughout the research and writing process, particularly Priscilla Reagan, Trevor Thrall, Gregory Koblentz, Dan Druckman, and the late Frances Harbour, who left us in December 2013. Many thanks also to GMU students Yong-Bee Lim, Leet Wood, and Kathleen Danskin, and Cornell University students Nicole Nelson and Zachary Newkirk, for tirelessly searching, finding, and checking data to support this book project. I'm also grateful to Marina Voronova and Dauren Aben for their research assistance in Russia and Kazakhstan. Many thanks also to Katherine Goldgeier and Robert Kulik for their editorial comments, and to Jeff Karr at the American Society for Microbiology Archives for his assistance in identifying and finding relevant documents about the American bioweapons program.

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Several colleagues and friends also generously offered their time to answer my questions or provide comments on several drafts and chapters of this book. Special thanks to Lynn Eden for reviewing several papers and highlighting ideas and themes that were worth pursuing. Many thanks to Alexander Montgomery, Jens Khun, and Jacques Hymans for providing insightful comments on several chapters of the book. I am grateful to Milton Leitenberg and Rod Barton for answering my questions about the Soviet and Iraqi bioweapons programs. Several other individuals—including one

with experience in a major U.S. biotech R&D firm, and others with experience in bioweapons offensive and defensive programs in the United States and Europe—should also be recognized, but I cannot name them to respect their wishes for anonymity. Do know that I very much appreciate your valuable insights.

I am extremely grateful to Roger Haydon for his editorial comments on an early version of the manuscript and for championing the book at Cornell University Press. I am also thankful to the anonymous reviewers who provided thoughtful commentaries and criticism that helped improve and sharpen the argument of this book. Many thanks also to Jamie Thaman and Kimberly Giambattisto for their editorial support during the final stage of publication.

I owe a debt of gratitude to my good friend and colleague Kathleen Vogel for her support throughout the research and writing process. Her insightful comments on several of the chapters were a tremendous help in sharpening the argument. Thank you also for introducing me to the social studies of science literature, where I discovered that several issues I was familiar with in my field of industrial economics also affected scientific work in the laboratory.

Finally, this book would not have seen the light of day without the unwavering love, support, and encouragement of my dear husband, Dennis Gormley. Dennis was my compass and a source of inspiration throughout this project. Our daily conversations provoked my thinking and were the origin of many new insights. Dennis also reviewed every single page of this book and helped me single out the few good ideas that it contained. Just as important, his focus and dedication to this project encouraged me to plow through and gave me encouragement when it was most needed. Dennis, I'm eternally grateful for your love and support.

Barriers to Bioweapons

CHAPTER 1

The Bioproliferation Puzzle

When at the end of 2011 scientists at the Erasmus Medical Center in the Netherlands announced their plan to publish a major finding about the H5N1 bird flu, they set off an unprecedented debate about the usefulness of scientific research with potentially serious security repercussions. The Erasmus team, led by Ron Fouchier, had created a mutant strain of H5N1 that spread more easily among mammals. Although only about six hundred humans are known to have contracted H5N1 in the last decade, 60 percent of those infected by the virus died from it. Thus, the new strain sounded alarm bells within the scientific community and security circles alike. Fouchier's indelicate public comments made matters worse when he declared that his team had "mutated the hell out of H5N1" to create "probably one of the most dangerous viruses you can make."[1] Several other experiments had previously been the subject of controversy, but the H5N1 case was different: it was the first time that the National Science Advisory Board for Biosecurity (NSABB) requested that scientific details be deleted before publication for fear that they might be used by terrorist groups.[2] For all the publicity that it garnered, the NSABB's request to halt publication did not foster a consensus about what type of research constitutes a security threat. The NSABB reversed its decision a few months later; Fouchier and his team resumed H5N1 research, putting an end to a yearlong global moratorium; and two years later, the debate remains deeply divisive.[3] But the key security question at the heart of the controversy remains unanswered: Would access to published documents suffice to allow replication of past work? If so, does this mean that the bioterrorism threat automatically increases with the progress of science?

In this book I argue that the answer to these two questions is negative. This is contrary to the belief, shared by many analysts and policymakers, that bioweapons development requires only the procurement of three easily accessible resources: biomaterials, scientific data, and equipment. Therefore, the question of what skills and what conditions would allow replication is not considered. Yet the analysis of past state and terrorist bioweapons programs

shows that producing a working bioweapon is not a simple process of material accumulation. The challenge in developing biological weapons lies not in the acquisition but in the *use* of the material and technologies required for their development. Put differently, in the bioweapons field, expertise and knowledge—and the conditions under which scientific work occurs—are significantly greater barriers to weapons development than are procurement of biomaterials, scientific documents, and equipment. Contrary to popular belief, however, this specialized bioweapons knowledge is not easily acquired. Therefore, current threat assessments that focus exclusively on the formative stage of a bioweapons program and measure a program's progress by tracking material and technology procurement are bound to overestimate the threat.

Understanding that the barriers to bioweapons are found not during the formative stage of a program but during the *sustenance* phase, when actual work with and processing of bio-agents commence, has several important implications. First, it requires us to transition from a definition of proliferation as a process of straightforward accumulation, in which procurement is the key variable, to one that emphasizes the sustenance phase of a program, in which knowledge and expertise are the key variables. Second, measuring the pace and success rate of a program requires a detailed understanding of what factors shape knowledge acquisition and use within that program. Finally, because the variables that truly affect the success of a bioweapons program are not currently addressed, the door remains open to proliferation. This reality dictates major changes in nonproliferation and counterproliferation approaches to address actual bioweapons threats. Current policies focus almost exclusively on preventing access to the troika of resources deemed essential for bioweapons development: material, scientific information, and technologies. By also targeting knowledge and the factors that affect its use, these policies could more effectively inhibit the growth of a weapons program and possibly bring about its collapse.

Untangling the Bioproliferation Puzzle

During the past decade, the disconnect between public perceptions of the bioweapons threat and empirical evidence has dramatically widened. Although several recent scientific feats seemingly support the idea that the biotechnology revolution is making it easier to achieve results unimaginable a decade ago, no terrorist group or state has seized upon these technological advances to produce bioweapons. Additionally, past state and covert terrorist programs had ample access to scientific information, equipment, and bioagents, yet most of them failed to develop an effective working weapon.[4] Even the 2001 anthrax letters call into question the idea that untrained individuals can easily produce biological agents. In spite of a decades-long ca-

reer in a premiere U.S. military laboratory, as well as access to anthrax bacteria and the associated information and technology needed for its production, the suspected perpetrator was only able to produce a low-grade powder. Further, although the powder became aerosolized, killing five people and injuring seventeen, it occurred not by intent but by virtue of the postal system's mail sorting machines. So why is bioproliferation still viewed as a simple input-output challenge in which the acquisition of material, scientific information, and technologies will somehow result in a working weapon?

Three misconceptions are at the heart of the current faulty assessment of the bioweapons threat. The first finds its roots in the use of the nuclear model as a starting point to assess bioweapons development. Put simply, because biological weapons do not face the same stiff material barrier as do nuclear weapons, they are deemed easy and cheap to produce. The second lies in the assumption that any biology-related knowledge is applicable to bioweapons development and that bioweapons expertise is easily acquired and used. The third assumes that new technologies will erase the technical barriers to bioweapons development, allowing even untrained individuals to achieve successful results.

WRONG MODEL, WRONG BARRIERS

The idea that biological weapons should not be equated to nuclear weapons has been suggested before, but mostly to emphasize the extraordinary destructive power of nuclear weapons,[5] not to highlight the unique nature of biological weapons. Yet there is a key distinction between the two weapons systems: they use materials of a decidedly different nature, which create barriers to entry at different points of their development process.

In the nuclear field, a key barrier to entry is located at the front end of the development process, at the stage of material acquisition. Achieving nuclear weapons is indeed conditioned by the ability to produce fissile material, which requires large facilities and specialized equipment. This suggests that once the procurement challenge is overcome, the development of a weapon is a straightforward process. A few scholars have denounced the technological determinism behind this view of nuclear proliferation, noting that nuclear weapons can hardly be reduced to the sum of their parts, because design, engineering, and mechanical problems have often been more vexing than material production.[6] This model, therefore, does not fully grasp the complexity of nuclear weapons development. Nevertheless, the fact that fissile material acquisition *does* constitute a major barrier to nuclear development gives current theories a certain realist cachet. Their policy prescriptions, which focus on raising barriers to material access by, for example, reinforcing export controls or designing counterproliferation policies that target equipment, also have value because they target an essential—albeit limited—part of nuclear weapons development.

When applied to bioweapons, however, the front-end/material-based nuclear model produces a distorted and even apocalyptic picture of the threat. Most analysts and policymakers stress that pathogens—viruses, bacteria, and toxins—can be isolated from nature or obtained commercially because they also have legitimate commercial or pharmaceutical use. They point out that equipment is essentially dual use and can therefore be readily purchased, while scientific publications provide ample descriptions of experiments and techniques that many believe can be easily replicated. To be sure, some experts emphasize that weaponization and dispersion of lethal agents constitute important and difficult stages of bioweapons development, particularly for terrorist groups. However, they also contend that advances in biotechnology will rapidly lower the technological threshold, and that new technologies and scientific processes, no matter how complex, will have the potential to be used for nefarious goals by states or nonstate actors.[7] Because the material barrier that impedes nuclear developments does not exist in the bioweapons field, bioweapons appear easier and substantially cheaper to produce, making their use by state or nonstate actors seemingly inevitable.

There is no doubt that this line of argument found a favorable echo after the terrorist attacks of September 11, 2001, together with the anthrax-laced letters sent to various American newspapers and politicians a few weeks later. News reports about the rapid succession of scientific achievements that seemed to be propelled by rapid advances in biotechnology provided more fuel to these apocalyptic prophecies. In addition to those brought on by the recent H5N1 experiment, fears of imminent bioterrorism were also raised in the aftermath of the inadvertent development of a virulent mousepox virus by an Australian team of scientists in 2001; the synthesis of the poliovirus in 2002 by a team of scientists at the State University of New York at Stony Brook, using off-the-shelf material and data available on the Internet; the construction of a bacteriophage using synthetic oligonucleotides, completed within two weeks in 2003 by the J. Craig Venter Institute (JCVI) in Rockville, Maryland;[8] the resurrection of the deadly 1918 flu virus in 2005; and the synthesis of the first self-replicating cell (*Mycoplasma mycoides* JCVI-syn1.0) by JCVI in May 2010. Other recent developments in the field of synthetic biology and bioengineering also seem to reduce bioweapons development to the assemblage of ready-to-use synthetic parts. For example, synthetic DNA sequences and ready-to-use molecular biology kits can be purchased from commercial companies at a rapidly decreasing cost.[9] Furthermore, since 2003, researchers at the Massachusetts Institute of Technology have called on a wide community of scientists and amateurs to produce standard short pieces of DNA, called "BioBricks." The project now offers a library of about five thousand biological parts, which can be assembled much like Lego pieces to create new synthetic constructs. Finally, seemingly further lowering the technological threshold, a growing community of do-

it-yourself amateur biologists manipulate or create new biological organisms and showcase their feats at international competitions or on Internet-based games.[10] Consequently, the argument goes, the already weak barriers to bioweapons development are breaking down, making it increasingly easier for even untrained individuals to replicate past work or exploit cutting-edge biotechnologies.

This line of argument raises an interesting puzzle. If bioweapons developments were so simple, more states and terrorist groups should have achieved satisfactory results. But historical evidence shows otherwise. The declining efficiency of nuclear programs highlighted in Jacques Hymans's *Achieving Nuclear Ambitions*[11] can also be observed in the bioweapons field: recent bioweapons programs have been less successful than their predecessors. The major distinction between the nuclear and biological weapons fields, however, lies in the fact that none of the past bioweapons programs have been completely successful. The Soviet Union, which had the largest and longest-running program, did not reach the level of accomplishment that its sixty-year lifespan and estimated investment of $35 billion might suggest. Soviet scientists successfully weaponized several classical agents, loading them into a variety of bombs, but according to recent evidence, their work on engineered pathogens—the program's main focus during its last two decades—did not extend beyond the exploratory phase. Additionally, Soviet scientists did not develop dedicated ballistic or cruise missile warheads, contrary to earlier claims.[12] The American program, arguably the second largest program after the Soviet Union's, cost about $700 million over twenty-seven years but resulted in only a small arsenal of bombs filled with half a dozen agents, and no ballistic or cruise missiles to deliver them. Other states and terrorist programs performed even more dismally. Iraq invested twenty years and over $80 million during the last five years of the program alone to produce ineffective bombs that would have destroyed most of the liquid agents they contained. South Africa devoted twelve years and over $30 million to its program while producing only poisonous substances for assassination purposes. Finally, the Japanese terrorist group Aum Shinrikyo spent six years and about $10 million trying to produce anthrax- and botulinum-based weapons but failed at every stage of these bioweapons' life cycles.

What the current conception of the bioweapons threat fails to grasp is the unique nature of bioweapons materials, which creates steep challenges not at the initial stage of material acquisition but later on in the development cycle, at the stage of material processing and handling. Put simply, the key barrier to bioweapons development is not at the formative stage of a program but during its sustenance. Unlike nuclear weapons, which rely on materials with physically predictable properties, bioweapons are based on living organisms or by-products of living organisms, which evolve, are prone to developing new properties, and are sensitive to environmental and

handling uncertainties. Their behavior, therefore, is unpredictable throughout all stages of development and use as a weapon, which imposes an extended trial-and-error process to acquire the skills necessary to solve problems that inevitably arise.[13] The unpredictability of living microorganisms has long been a challenge in the pharmaceutical and bioweapons fields. In the 1940s, Pfizer's John Smith characterized the mercurial character of living organisms as follows: "The mold is as temperamental as an opera singer, the yields are low, the isolation is difficult, the extraction is murder, the purification invites disaster, and the assay is unsatisfactory."[14] Similarly, in the bioweapons field, Soviet and U.S. bioweapons scientists found that some strains do not respond well to manipulation and might lose their virulence as a result, compromising their use as weapons.[15] The unpredictability of biomaterials has not been reduced by the advent of new technologies. For example, gene synthesis companies, which use highly automated processes to produce strands of DNA, routinely yield faulty materials due to errors that can naturally occur in the synthetic process, and the design software they use cannot always identify and correct these errors.[16] Similarly, bioengineering projects, such as BioBricks, have to face the reality that most of the synthetic parts produced do not work: when the bioparts are assembled, unexpected interactions or incompatibilities occur. The parts are also subject to variations in growth conditions.[17] The new technology therefore remains captive to the complexity of living systems, and in spite of the progress made in understanding their functions and composition, the process of creating and maintaining viable organisms still retains a great deal of mystery.[18] Consequently, this unpredictability places greater emphasis on possessing the unique skills necessary to handle highly capricious biological agents and maintain their desirable properties throughout the development process.

In the bioweapons field, these challenges are particularly acute as the agent moves down the development process toward weaponization. One such stage is scale-up. Biomaterials do not scale up easily. Yet the passage from a laboratory sample to larger quantities, whether a few gallons used in a terrorist program or industrial quantities used in a state program, stands as a critical stage of bioweapons development. Because scale-up is not a linear process, increases in quantity must occur gradually. Each increase, however, entails new challenges that impose changes to the production protocols. For example, it took four years to scale up the Soviet smallpox weapon and five years for the anthrax weapon. In the latter case, unexpected challenges necessitated a complete review of the production parameters, from the type of culture media used to the temperature setting, or the type of safety equipment required. Each modification entailed additional research and testing. Yet the lethal characteristics of the weapon could not be maintained, which necessitated the influx of a new team of experts and a reconfiguration of the production process. These changes resulted in a weapon that was dramati-

cally different from the original designed by the Kirov institute.[19] In addition, production and scale-up often subjected bioagents to contamination, which caused multiple delays and failures both in the U.S. and the Soviet bioweapons programs. Pharmaceutical and biotech companies also routinely endure such failures due to the complexity and sensitivity of biological organisms.[20]

Complicating matters, external factors that cannot be easily identified or quantified can also interfere with experimental work.[21] For example, within the U.S. bioweapons program, the production of biological material was routinely subject to unexplained failures whenever production was interrupted to service or decontaminate the equipment. On these occasions, plant technicians at Fort Detrick—the main facility of the U.S. bioweapons program—experienced on average three weeks of unsuitable production. The scientific staff could not identify the causes of such routine failures and could only assume that either a contaminant had been introduced during the service or cleanup, or that technicians unwittingly changed the way they were doing things and unconsciously corrected the problem several weeks later.[22]

Successful scale-up also requires the intervention of interdisciplinary teams with a variety of skills, whose work must be carefully integrated and coordinated. Integration and coordination are particularly important in large programs, which may involve thousands of individuals and hundreds of facilities (as in the Soviet program), but also in smaller ones, such as the Iraqi program, which involved about one hundred people. In the Soviet bioweapons program, many failures and project delays resulted from insufficient integration and coordination of people and stages. For example, when the Russian bioweapons institute Vector was tasked to develop a large-scale production process for the Soviet smallpox weapon, facility director Lev Sandakchiev requested the help of experts from the military facility at Zagorsk, Russia. Although he was a smallpox specialist, and Vector's personnel included several virologists, Sandakchiev felt that there was insufficient expertise in his institute to achieve the objective. The dispatched Zagorsk experts provided the needed help, but due to Soviet restrictions on information exchange between military and civilian scientists, they were unable to fully integrate with the existing team, extending completion of the work to four years.[23] In the Iraqi case, the program not only did not benefit from the gamut of expertise required to ensure successful scale-up and weaponization but also failed to integrate the different stages of a weapon's development, consequently leading to the creation of ineffective bombs.

In addition, unlike nuclear weapons, which can use only two sources of material—highly enriched uranium and plutonium-239—bioweapons development can exploit a large number of agents that vary in type (bacteria, viruses, toxins), properties (virulence, infectivity, transmissibility), and ease of culturing.[24] Each agent also includes several strains with varying properties,

further complicating bioweapons development. For example, the botulinum bacteria, which has been considered for bioweapons work in most state and terrorist programs, includes hundreds of strains, but only a handful of them actually produce toxins—a requirement for bioweapons work. Aum Shinrikyo spent about three years trying to isolate a toxin-producing strain of the bacteria but to no avail. Furthermore, botulinum toxin does not always withstand dissemination and may lose its toxicity when released as an aerosol.[25] Further complicating matters, the expertise acquired while working with one agent does not necessarily transfer to another microorganism. This lack of knowledge transferability limits the ability of a state or group to transition easily to new types of bioweapons should their work with one agent fail to produce tangible results. In bioweapons programs, work with a new agent also requires prior experimentation with a simulant to anticipate potential problems and reduce the risks of contamination when working with pathogenic agents. Therefore, transitioning to a new organism entails a lengthy period of knowledge acquisition, which would necessarily delay progress.

Consequently, the nuclear model that focuses on the formative stages of a program and its material acquisition completely misses the unique character of bioweapons development. Due to the fragility of living microorganisms, possessing the skills to handle and manipulate them throughout the development process is a greater barrier to entry into the bioweapons field than is material procurement.

THE FALLACY OF UNIVERSAL, FREE-FLOWING KNOWLEDGE

The second tenet of the current view of bioweapons proliferation is that science-based knowledge and technology are universal, independent of context, impersonal, public, and cumulative. As a result, knowledge spreads easily, and written documents, such as scientific publications, weapons designs, or scientific protocols, constitute complete representations of a technological artifact, thus allowing the replication of past work, even by untrained individuals.[26]

In reality, however, knowledge is far from free flowing. Studies of knowledge transfer in various technological environments, including bioweapons technology, show that access to scientific documents does not guarantee their successful use, even by experts. This is so because scientific documents include only a small fraction of the knowledge produced within a program or scientific experiment. Indeed, technical knowledge results from a process of experimentation that produces both explicit and tacit knowledge. Whereas explicit knowledge can be codified and encapsulated in different physical formats that are easy to transfer—protocols, formulas, or designs—tacit knowledge is constituted of know-how: unarticulated skills or practices that cannot be reduced to a written form and are often personal, local,

and context specific. Their transfer requires direct and prolonged interaction among people, and their use in a new location requires adaptation to the new site. In addition, complex projects such as bioweapons development involve teams of scientists and technicians, representing different disciplines, who, through their interactions and cooperative work, produce a different form of knowledge—known as communal knowledge—which is shared by all team members but possessed entirely by none. As a result, even individual experts possess only a limited knowledge of a whole weapon and its development. In addition, unlike explicit knowledge, which has a long shelf life, tacit knowledge decays over time if not sustained through practice.

Replicating past work using scientific documents alone, therefore, cannot be achieved without access to the corresponding tacit skills and the related communal knowledge. It is worth noting that whereas the scientific feats of the past decade have often been associated with their principle investigators, they in fact involved teams of scientists having unique expertise, who worked together for an extended period of time. For example, the resurrection of the 1918 flu was conducted by a team of scientists from four institutions—the Centers for Disease Control and Prevention in Atlanta; the Armed Forces Institute of Pathology in Washington D.C.; the Mount Sinai School of Medicine in New York; and the U.S. Department of Agriculture—each performing a specific stage of the experiment. In addition, the work took ten years to complete, from 1995 to 2005. Similarly, the H5N1 experiment was conducted by two institutions—the University of Wisconsin–Madison and the Erasmus Medical Center in the Netherlands—each using different methods and different expertise. Laboratory work at the Erasmus center, for example, took about four years to complete, following the ten years required to prepare the experiment.[27] In the case of the Soviet anthrax weapon, Soviet scientists at the production plant in Stepnogorsk where scale-up took place had access to about four hundred pages of documentation describing production protocols and other essential details. But this did not obviate the need for a lengthy period of experimentation and testing. Furthermore, progress in scaling up the weapon began to be made only after the authors of the weapon joined the production team, along with about sixty other experts.[28]

Tacit knowledge aside, written or published scientific documents are also often incomplete because they fail to emphasize essential aspects of scientific success, such as the contingencies associated with key stages of an experiment, the characteristics of the equipment—some scientists have their equipment custom-made to increase the rate of success for certain manipulations—or the laboratory routines that constitute essential parts of the scientific discipline and success.[29] Experimental work also involves making changes on the fly that are not necessarily recorded, either for lack of time or because the scientists do not recognize the importance of these

changes for experimental success. Without such details, reproduction is made even more complicated.

Finally, concerns about the risk associated with publication of dual-use research hinge on two other erroneous assumptions. First is the assumption that expertise acquired in a civilian laboratory can easily be applied to bioweapons work. Here again history belies this belief. For example, when the Vector institute was established in Russia in the 1970s, most of its personnel was hired from the nearby Novosibirsk State University and included several virologists as well as smallpox experts. Yet the scientific team did not start developing bioweapons until five years later, because the scientific and technical staff needed to both familiarize themselves with the methods and technology used for working with pathogenic agents, and learn from military scientists with the appropriate bioweapons expertise. In the U.S. program, the learning curve was even steeper, because unlike their Soviet counterparts, the scientific staff—also mostly originating from the university system—had no prior bioweapons expertise to rely on simply because the program was started from scratch in 1942. As a result, the learning phase in the American program lasted about twenty years.

The second assumption is that innovations achieved in the laboratory can be easily fashioned into a harmful agent or a bioweapon. In fact, past bioweapons work, as well as current pharmaceutical efforts, show that transforming a scientific concept developed in the laboratory into a product that has a specific applied purpose and that functions reliably and effectively can take several decades and require the intervention of a wide array of expertise.[30] For example, within the Soviet bioweapons program, the development of a strain of plague resistant to antibiotics took twenty years to achieve and involved teams at three institutes. In addition to the scale-up challenges previously discussed, bioweaponeers also face the challenge of developing a delivery mechanism that will protect living organisms and toxins from degradation due to environmental conditions. Iraq's and Aum Shinrikyo's weaponization failures are instructive in this regard, as are the American program's meager results in this area. Therefore, laboratory successes are not equivalent to successful application to a specific purpose. Specialized skills acquired through hands-on involvement in production and weaponization work are needed.

Thus, scientific innovations and their corresponding documents require extensive interpretation and judgment from users other than their authors, which in turn necessitates the possession of prior base knowledge and ideally the ability to work in close cooperation with the documents' authors. In addition, applying these scientific findings to bioweapons developments requires the acquisition of bioweapons expertise, which can take years. These conditions constitute major obstacles for replication of past work, particularly for untrained individuals operating under covert conditions.

THE FALLACY OF TECHNOLOGY AS A BLACK BOX

The third pillar of the current view of bioweapons proliferation relies on the so-called biotechnology revolution. Because they automate processes that previously required the manual intervention of skilled personnel, new technologies are believed to facilitate replication of past work and allow their application to bioweapons development. What's more, economic globalization and the rapidly decreasing cost of such technologies are deemed to be key factors in accelerating their diffusion, making it almost impossible to rein in bioweapons proliferation. The narrative behind the biotechnology revolution rests on two important premises: (1) new technologies and equipment are black boxes, with an input and an output, which can be used by any user, irrespective of their technical skills; and (2) technology developments result in a gradual deskilling of technological and scientific work. Therefore, machines and their accompanying instructions become the embodiment of human knowledge, captured and codified for easier use by less experienced individuals.

If knowledge was completely embedded in machines, all users would achieve equal results whatever their level of expertise. Empirical research shows that this is not the case. Instead, technologies, very much like written documents, constitute imperfect representations of their designers' knowledge, and although they may simplify some tasks, they require from their users extensive experimentation, interpretation, and adaptation to a new location to achieve successful results. This is due to the fact that new technologies rarely automate all aspects of a task, requiring scientists to perform some tasks manually. Furthermore, machines, however sophisticated, are also prone to errors, requiring their users to possess the skills to identify and correct problems. For example, the ready-to-use kits sold with the polymerase chain reaction (PCR) machine allow scientists to conduct various manipulations of DNA samples. Yet the kits do not always work as expected, requiring their users to develop the skills needed to correct problems or call on a community of colleagues to help solve these problems.[31] Similarly, the process of gene synthesis, which is highly automated, still necessitates manual intervention from skilled scientists and requires them to have sufficient knowledge at the outset to determine what equipment and methods will best serve their objectives.[32] Further eroding the biotechnology revolution concept are empirical analyses showing that some of the scientific experiments that have raised alarm bells in the past decade do not owe their successes to the use of new technologies. Rather, they are explained by the painstaking accumulation of knowledge by teams of scientists with unique skills.[33]

These observations suggest that replication of past work and the use of new systems for malevolent purposes are not as straightforward as news reports make them out to be, particularly for untrained individuals. The

adaptation of current scientific achievements for bioweapons purposes would require skills not easily acquired. By placing the emphasis on procurement, the current proliferation model for bioweapons creates unnecessarily apocalyptic prophecies and, more importantly, shifts public attention away from the variable that has a greater effect on a program's outcome—knowledge acquisition and use—thus leaving a source of proliferation unaddressed. The current model also fails to provide adequate tools to more accurately assess a bioweapons program's developmental timeline and chances for success. With material procurement as the only variable taken into account, the implication is that with equal access to the three main ingredients—biomaterials, scientific documents, and equipment—programs should be equally successful within similar time frames. History suggests otherwise: in spite of having access to the main ingredients, ample funding, and substantial determination, some past programs failed at every stage while others succeeded only partially, and their time frames varied substantially.

Therefore, we need a new analytical model that can not only better explain the distinctions between various historical cases but also provide adequate tools to assess the reality of future threats. For example, what explains the American program's modest achievements in weaponization, whereas the program is generally considered to have been successful at the scientific level? Why didn't Soviet attempts to develop new genetically engineered pathogens go beyond the exploratory phase, in spite of decades of work and seemingly unlimited resources? Why were the most recent covert programs—in Iraq, South Africa, and Japan (Aum Shinrikyo)—equally unable to produce a working weapon, in spite of what would seem more-than-adequate circumstances? The current model assigns the same level of imminence to most programs and generally overstates the threat. In addition, it provides good reasons for potential enemies to embark on bioweapons development, at the risk of allowing them to overcome the barriers to bioweapons development.

Argument in Brief

The new analytical framework that I propose in this book offers a toolbox of key variables to better assess the progress, timeline, and outcome of state and terrorist bioweapons programs. My analytical framework defines the sustenance phase of a program as the key stage of bioweapons development, in which knowledge acquisition is the key variable. I also offer two sets of factors that affect the use of knowledge—those from within a program (endogenous variables) and those from the outside (exogenous variables)—the combination of which results in different speeds and outcomes.

At the core of this framework is the idea that technology results from the interaction among individuals who combine their respective expertise to

produce a working technological artifact. A program's success will therefore depend on these individuals' ability to cooperate, exchange information, learn from one another, and institutionalize knowledge. Because knowledge transfer depends on the quality and frequency of individual interactions, the manner in which a program organizes and manages its resident-expert knowledge will also influence scientific outcomes. Consequently, a bioweapons program's structural and work organization, its management style, and the social context within which knowledge is created constitute the endogenous variables that figure into a program's success or failure. Managerial and organizational issues shape the outcome not only in large state programs but also in smaller state and terrorist enterprises, simply because the development of bioweapons requires an organizational and managerial model that promotes knowledge creation and sustainment. Without such a model, slow progress or program failure is likely. A better understanding of organizational and managerial factors also provides insight into why differences in achievement by various facilities within an overall program frequently occur.

The second key tenet of the proposed framework is that weapons programs do not happen in a vacuum; they frequently depend on their external context. Several such exogenous variables influence the conditions in which scientific work occurs. Foreign technical assistance is one of these variables. Its importance for proliferation has not escaped political scientists and policy analysts, who generally believe it has a positive influence on the direction and pace of a program. However, I suggest that procurement of material and even high-quality expertise should be analyzed through the lens of three main factors: the absorptive capacity of the recipient country,[34] the organizational makeup of the program, and the program's managerial characteristics. In other words, it is not merely the provision of technical assistance that allows a state or group to make progress but also the type and timing of the assistance. If the recipient cannot absorb the assistance, or if the organization or management of a program does not allow proper integration, technical assistance may in fact lead to delay or failure. Two other exogenous factors—the priority political or group leaders devote to a program, and a program's economic circumstances—also affect a program's outcome, not only because they have an impact on programmatic and funding decisions but also because they influence the continuity and stability of scientific work—two essential conditions for the accumulation of knowledge. These factors may also generate scientific behaviors that can produce bad science. Finally, in some cases, the location of a program can promote or constrain its development and the successful use of technologies by affecting the properties of the material used in laboratory work. For example, a simple change in the pH of water and the use of different suppliers of laboratory materials can cause experiment failure.

Most important to a program's timeline and outcome is the way in which states or terrorist groups integrate these two sets of variables: social,

organizational, and managerial factors that influence knowledge acquisition and scientific work from within; and exogenous variables that influence achievements from the outside. In theory, a program is successful if it can ensure the efficient use of its material resources; create conditions that ensure that knowledge and unarticulated skills are acquired, used, and shared throughout the program; adopt an organizational and managerial model that will promote cooperation, information exchange, and innovation; fashion a social environment that enhances personnel cooperation; and manage exogenous factors to maximize their benefits while limiting their potential negative impact on the program's outcome. As we shall see, these conditions are difficult to achieve, and none of the programs analyzed in this book have been able to create such ideal conditions. This is especially so for programs operating under the constraint of covertness, whether state or terrorist sponsored, because covert programs face greater limitations on information exchange, organization, management, and their ability to deal with exogenous factors.

Additionally, the factors that influence the sustenance phase of a program interact with one another and can reinforce or dampen their respective effects. It is important, therefore, to analyze these variables in combination and in context, not independently. For example, programs that start with an apparent handicap—such as insufficient political support or financial resources, as did the U.S. bioweapons program—may decrease the negative effects of such insufficiencies on the overall outcome of the program by boosting the positive effects of other variables, such as adopting a favorable organizational and managerial model. By contrast, programs that appear to operate under ideal conditions, with no restrictions on material, financial, and personnel resources, as was the case for the Soviet bioweapons program, may not achieve results that are commensurate with the resources invested in the program because of the negative impact of their organizational or managerial conditions and their economic environment.

Using this new framework to assess future bioweapons threats can be complicated by the fact that we do not always have access to information about the key variables. Nevertheless, by using this framework, we can interrogate the information we do possess in new ways. Also, understanding what we do not know can help focus intelligence-collection efforts. In addition, adopting an analytical framework that emphasizes the sustenance phase of weapons programs is more useful for understanding why some programs succeed while others fail. This new framework also has important policy implications. By shedding light on underappreciated variables of bioweapons proliferation, policymakers and analysts alike can design new nonproliferation and counterproliferation policies that take into account a program's specific circumstances and increase the chances that such policies will more efficiently delay, disrupt, or possibly even terminate a program.

Road Map

This book is composed of three parts. Part one—chapters 1 to 3—lay down the theoretical concepts that support the book's main arguments. In chapter 1, I have introduced the book's main argument and highlighted the importance of a better understanding of the sustenance phase of bioweapons programs to evaluate their timeline and outcome. In chapter 2, I explore the nature of knowledge, drawing on concepts developed in the fields of economics, science and technology studies, management, and cognitive science that together delve into the contextual determinants of technological developments, including weapons development. This chapter discusses the different forms of knowledge—explicit and tacit—how they are acquired, transferred, and used; and how the workplace environment can help or hinder innovation and affect the successful completion of a technical project. By showing that technical knowledge is stored in interdependent reservoirs that may erode over time, the chapter dispels the notion that scientific and technical knowledge is universal and free flowing. Chapter 3 extends the interdisciplinary analysis to the identification of the variables that impede or facilitate knowledge use and bioweapons development. Although each variable can be ascribed a negative or positive value and has a clearly identifiable impact on a program, it is the interaction of all the variables that ultimately affects a program's pace and outcome. The effects of one variable may indeed be enhanced or dampened by the effects of another.

In part two, I apply the theoretical concepts to an analysis of five case studies of bioweapons programs: the American (chapter 4); Soviet (chapter 5); and Iraqi, South African, and Aum Shinrikyo programs (chapter 6). These case studies offer different combinations of variables and demonstrate how the interplay of specific endogenous and exogenous variables affect these programs' paces and outcomes differently, notwithstanding the availability of material, human, and financial resources, as well as the size and lifespan of the programs. What's more, because bioweapons became illegal after the signature of the Biological Weapons Convention (BWC) in 1972, all programs but for America's, which was terminated in 1969, were subject to the added requirement of avoiding detection by means of extensive covertness, which dictated the use of organizational and managerial models that dramatically impeded scientific progress and precipitated failure in the South African, Iraqi, and Aum Shinrikyo programs.

Finally, in part three (chapter 7), I draw out the policy implications that flow from the book's analysis in four distinct policy domains: first, fashioning a more effective policy of bioweapons dissuasion; second, adjusting current nonproliferation and counterproliferation policies to improve their effectiveness, which includes revisiting the idea of a BWC protocol; third,

developing more appropriate threat assessment tools to detect the state of suspect bioweapons programs; and finally, improving policies dealing with the flow of truly valuable bioweapons knowledge—such as through better brain-drain prevention—while avoiding the restriction of knowledge conveyed in open scientific journals.

CHAPTER 2

The Acquisition and Use of Specialized Knowledge

At a meeting in Geneva in December 2011, former U.S. secretary of state Hillary Clinton warned of a potential bioterrorism threat, saying, "a crude, but effective, terrorist weapon can be made by using a small sample of any number of widely available pathogens, inexpensive equipment, and college-level chemistry and biology."[1] Her statement reiterates a belief common since 2001 and now shared by most policy experts and political scientists alike: scientific knowledge is cumulative, is easy to acquire and use, and does not depreciate over time. Yet the academic and practical evidence suggests that the acquisition and effective use of specialized knowledge may not be as simple as Clinton suggests. Literature in the fields of economics, knowledge management, cognitive science, and science and technology studies indicates that specialized knowledge is not easy to acquire, use, or transfer because much of it is tacit, local, and collective in nature. In addition, scientific knowledge pertaining to a technological artifact is rarely stored in a central location. It is more often held in various interdependent reservoirs, each containing a portion of the relevant knowledge. Moreover, knowledge decays over time if it is not used or transferred to the next generation. These factors raise questions about whether an untrained terrorist could in fact produce a biological or some other weapon of mass destruction (WMD) using easily accessible scientific data and material. As a matter of fact, studies of past weapons programs show that even trained scientists encounter tremendous obstacles in replicating earlier work. This chapter explores how different types of knowledge are acquired and transferred, how new knowledge-based skills are produced and mastered, and how knowledge is stored and eroded over time.

The Tacit, Local, and Collective Nature of Knowledge

Many political science and policy experts routinely suggest that scientific knowledge, particularly that relating to WMD development, is fairly explicit.

They say scientific documents spell out enough knowledge about a technological artifact, such as a weapon, to provide the data sufficient to replicate past work or advance a covert program. This simplistic view of knowledge contrasts with the more nuanced understanding in fields where the study of knowledge and learning has a long history: economics, cognitive science, knowledge management, science and technology studies, and even philosophy. In the 1940s, for instance, philosopher Gilbert Ryle distinguished between "knowing that" and "knowing how," separating theoretical knowledge that can be verbalized from practical knowledge that cannot be translated into words.[2] A few years earlier, economist Friedrich Hayek drew the same distinction by emphasizing the existence of "unrecognized knowledge" and its importance in decision making.[3] In the field of science and social sciences, Michael Polanyi famously wrote that "we can know more than we can tell," referring to the tacit dimension of knowledge, which relies on personal judgment and other intangible sensory cues and influences the process of scientific discovery.[4] In cognitive science, John Anderson, building on previous work, differentiated between "declarative knowledge"—made of facts that can be articulated—and "procedural knowledge"—a set of skills or knowledge about "how to do things," acquired gradually and only by doing.[5] These various disciplinary fields have produced a rich body of literature identifying the different forms of knowledge, their modes of acquisition, and the conditions best suited to ensure learning.

FORMS OF TACIT KNOWLEDGE

Although these disciplinary fields use different terms to identify various forms of knowledge, there is general agreement that knowledge is composed of two types: tacit and explicit. Explicit knowledge is that which can be translated into a written form or verbalized. Equations, numbers, laboratory protocols, recipes, designs, instructions, and scientific publications are good examples of explicit knowledge. Because explicit knowledge can be imprinted onto a physical support (be it paper or computer), it can be stored for long periods of time, copied, and transferred through impersonal means, such as e-mail messages or computer files. In contrast, tacit knowledge is composed of unarticulated skills, know-how, practices, tricks of the trade, or visual and tactile cues that are more personally held. Because of its personal and intangible nature, tacit knowledge is less easily copied or stored on a physical support. Instead, it is stored in the brains of individual scientists, technicians, or engineers, which limits opportunities for its transfer. When transfer occurs, it requires direct interaction between individuals, often in the form of a long-term master-apprentice relationship. Even in such intimate conditions, however, transfer may be hampered by the fact that tacit knowledge is itself composed of different forms that may not be recognized by their owners.

Through his analyses of various scientific and technical fields, sociologist of science Harry Collins devised a useful typology of tacit knowledge that can be grouped into two categories.[6] The first category includes forms of tacit knowledge that could conceivably be made explicit or verbalized but require direct contact between people for their identification and transfer. The second group includes types of tacit knowledge that cannot be or are not made explicit either because they rest on deeply unconscious mechanisms or because they are too complex to be effectively translated into words. Their transfer also requires direct interaction between individuals and, more importantly, a long-term collaborative engagement.

The first kind of tacit knowledge includes "concealed knowledge" and "mismatched salience." Concealed knowledge refers to knowledge that can be verbalized but remains tacit because it is concealed from outsiders. Apart from infrequent cases of voluntary concealment, in which the owner purposely withholds essential data—such as a scientist who withholds important details of an experiment from a publication to prevent quick replication by others—involuntary concealment is of greater interest here. For example, details of an experiment might be deleted from a publication due to space restrictions, even though the author does not intend to conceal data. In other cases, concealed information consists of tricks or practices known only by their creators, which are nonetheless essential in achieving successful results. For example, in an article discussing the measurement of the quality (Q) of sapphire—a step in laser developments—Collins shows that Western scientists could not replicate the high measurements achieved by Soviet scientists during the Cold War, although they all used the same well-known method: suspending the sapphire at the end of a thread rubbed with animal grease. Only after the breakup of the Soviet Union, by virtue of a scientific exchange, did a Russian scientist reveal to his British counterparts a trick he used in his Soviet-era laboratory: instead of using animal grease, he used human skin oil. By rubbing the thread under his nose or behind his ears, he collected his own skin oil, a practice that contributed to achieving higher measurements. British scientists experimented with this trick, and a year later they were able to achieve measurements similar to those obtained by Soviet scientists.[7]

Another form of tacit knowledge that could, in principle, be verbalized is mismatched salience. Mismatched salience refers to situations in which individuals do not speak the same language, in the sense that they do not share the same mental frames or technical knowledge. As a result, they think about and address problems in different ways, making their communications mismatched. As Collins puts it, scientist A does not know how to explain things to scientist B, and scientist B does not know what questions to ask, thereby leaving out "some essential piece of explicable knowledge."[8] The problem can be identified and solved when the scientists observe each other in action.

The second category of tacit knowledge includes "unrecognized/unrecognizable" knowledge and "ostensive" knowledge. A scientist who does not realize he or she is using certain procedures or "tricks" that are important for experimental success is tapping unrecognized knowledge. Transfer of such knowledge can occur only when two scientists work together. However, neither scientist may be aware he or she has passed on or received important knowledge through collaborative work. There is a debate in the literature about whether unrecognized knowledge can be made explicit or will remain forever unrecognizable because it rests on deeply unconscious mechanisms. The answer probably lies in the circumstances. Some scientists may be doing things in a certain way that can be visually identified by someone working with them and eventually made explicit. In other cases, scientists' way of doing things may escape visual or other sensory faculties, remaining deeply unconscious for both the practitioner and the observer and being transferred only through an unconscious emulation.

The other form of tacit knowledge in this category is ostensive knowledge. Ostensive knowledge is an idea, a concept, or a process that can be expressed in a diagram, an image, or an artifact, but is too complex to be entirely encapsulated or captured into words. The transfer of such knowledge requires pointing to an object or a practice, sometimes requiring the receiving party to touch or observe an artifact at various angles, to grasp the concept or idea.[9]

ACQUISITION OF TACIT KNOWLEDGE

Although the transfer of tacit knowledge requires direct contact, the acquisition of that knowledge does not occur instantly; it often involves a long-term and painstaking process of learning. Even in the case of concealed knowledge, for which one would assume that once the information is revealed, the acquisition and successful use follow rapidly, learning to use the revealed information can take several months and entail many failures. For example, in the case of the Q of sapphire mentioned above, it took a year before British scientists could replicate Soviet time measurements. One of the reasons for this delay was the need for British scientists to experiment with the new practice of using human skin oil. Scientists in the British lab had different skin types—dry, oily, just right—and finding the one with the right oil meant testing all of them.[10] In addition, deciding precisely what amount of skin oil is good enough for a successful experiment is a matter of judgment and experience. Even when tacit knowledge can be verbalized, its use can be fraught with obstacles because portions of the knowledge may continue to escape codification. As a result, its acquisition may involve a long-term trial-and-error process, during which individuals build a personal mental library of experimentations, allowing them to gradually and often unconsciously adjust the way they do things to reach success. Indeed, why they achieve success at a certain point often remains elusive, because in

most cases, scientists do not see any difference in the way they apply the technique on the first day and on the day they finally reach success.[11]

Learning the forms of tacit knowledge that cannot be verbalized is even more complicated, because the novice cannot benefit from the conscious guidance of the teacher. In this context, the passage of the skill from one individual to another requires not only direct contact but also a lengthy apprenticeship. The acquisition of the skill by the recipient may follow different processes: learning by emulating or learning by doing. In the first process, scientist B observes scientist A and emulates him until the skill is acquired. Emulation can result from the conscious observation and replication of a specific way of doing things. For example, in one laboratory, a new postdoc introduced a specific way of shaking a test tube, which other researchers observed and quickly adopted because the gesture was associated with greater experimental success.[12] Emulation may also occur without anyone understanding or knowing that the knowledge has been transferred and learned.

Learning by doing is the process required to learn motor skills—skills dependent on body movements that can only be acquired through personal practice. A classic example of motor knowledge is riding a bike. Although the concept of riding can be explained in writing or orally with various degrees of sophistication, understanding the concepts of speed and balance does not enable someone to ride a bike. Only personal experimentation, with various degrees of success and failure, will lead to the acquisition of the skill. The case of the Q of sapphire experiment is also an example of motor-skill learning.

Science policy scholar Kathleen Vogel describes another example in the field of biology in her analysis of the 2002 synthesis of poliovirus by a team of virologists at the State University of New York at Stony Brook. One of the key stages of the polio synthesis involved producing a cell extract required to grow the virus. To produce the cell extract, scientists use a well-known technique of crushing bovine serum cells in a dounce homogenizer, a sort of mortar and pestle. Although the technique is commonly used and seemingly simple, the production of a good cell extract depends on how much strength one applies when crushing the cells: if a scientist crushes too hard, the cells are destroyed; if the scientist does not apply enough strength, the cells are not crushed enough. In both cases, the cells cannot be used to grow the virus. Therefore, applying the right amount of strength is key, but this is a skill learned only through individual practice. At the Stony Brook laboratory, some scientists and technicians were better at it than others, and it could take several weeks or months to make a good extract. For some, it can take several years to acquire the technique.[13]

In other cases, developing specific sensorial cues requires learning by doing. For example, in an article discussing the hybridoma technology—used to create hybrid cell lines for the production of monoclonal antibodies—sociologists of science Alberto Cambrosio and Peter Keating show that a

crucial step in the technique is the transfer of the hybridomas from one 96-well microplate to another to keep them alive. The transfer, however, must take place only after the hybridomas have spent enough time in the original plate to secrete the required antibodies. Determining the right time for transfer requires the scientist to develop visual and other sensorial cues by observing the form and size of the cells and the color of the culture media to determine whether the cells are viable. What constitutes a viable cell, however, cannot be clearly measured or expressed. The determination relies entirely on the scientist's experience and personal judgment. To make that judgment, scientists use very imprecise terms, such as "the cells look happy" or "unhealthy."[14]

PERSONAL, COMMUNAL, AND LOCAL KNOWLEDGE

Because of its mode of acquisition, tacit knowledge is deeply personal: individuals acquire it through personal and sometimes lonely experimentation, a process that can introduce numerous modifications into well-known, explicit methods and gradually transform them into a set of personal practices. It would be a mistake, however, to assume that all tacit knowledge is personal and embedded exclusively in the brains of individual scientists.

The development of complex products—such as automobiles, aircraft, or weapons systems—requires large teams of scientists, technicians, and engineers from a wide array of disciplines and with specific skills. Such projects are usually divided into a series of stages, integrated across functions. They call on the expertise of interdisciplinary teams, in which each individual contributes his or her personal knowledge to the development of the complex product. The final product is therefore a team effort, not the result of a scientist working alone. For example, the U.S. biological weapons program involved not just microbiologists and veterinarians, but also mechanical and electrical engineers, chemists, aerobiology experts, and statisticians, among others. The U.S. nuclear weapons program employed theoretical and experimental physicists, as well as experts in explosives, metallurgy, mathematics, and even biologists and entomologists.[15] The hybridoma technology discussed earlier also requires knowledge in different disciplines, such as immunology, immunochemistry, biochemistry, virology, and bacteriology.[16] Through their contribution to the larger technical goal, teams of individuals produce a new form of knowledge—communal knowledge—that is spread among all contributors, but no one individual possesses the whole knowledge.

Several studies have also emphasized the local character of knowledge.[17] Because it is created within a specific environment, by a specific set of individuals, and with a specific infrastructure, knowledge cannot be easily transferred to a new location. Some studies have shown that the use of data and technology in a new location frequently requires adapting it to the new site.[18] For this adaptation to succeed, it often requires the presence or in-

volvement of the original scientific author(s) to guide the adjustment. For instance, within the Soviet bioweapons program, despite receiving hundreds of pages of scientific information on the production of the Soviet anthrax weapon designed by the Kirov bioweapons laboratory in Russia, the Stepnogorsk bioweapons production plant in Kazakhstan failed to produce an anthrax weapon based on this information after two years of repeated attempts. Only with the addition of sixty-five scientists from two Russian facilities at Kirov and Sverdlovsk, including the authors of the weapon from Kirov, and three more years of interpretation and modification of the original protocols, did the Kazakh facility succeed in producing an anthrax weapon, one that proved to be dramatically different from the Kirov weapon.[19]

Similarly, in his analysis of early laser developments in the late 1960s and early 1970s, Harry Collins emphasizes the fact that despite the availability of a wide literature on the subject, including scientific articles and conference presentations by those who actually built lasers, no laboratory had been able to produce a laser using written data alone.[20] In his study, Collins indicated that replication was possible only after some exchange of experience occurred between laboratories, via either personal visits or personnel transfers (research fellowships, student placements, periods of work at source laboratory). The number of exchanges allowing replication at a new site varied, depending on the expertise already available at the receiving site. Yet even when the receiving party was allowed to closely examine the machine in the source laboratory, failures occurred repeatedly. Collins notes that sometimes the source laboratory personnel did not fully understand the parameters of the machine and thus could not transfer knowledge they did not have. In some cases, elements judged to be insignificant by source laboratory personnel proved to be essential as they experimented with the technology. Scientists also noted that the transfer of knowledge occurred only with people who had actually built a laser: when the information was provided by individuals with the appropriate academic background but no experience in building lasers, replication attempts failed.[21]

Such mechanisms were also noted in the nuclear field.[22] In their analysis of the U.S., Soviet, and British nuclear programs, sociologists of science Donald MacKenzie and Graham Spinardi describe how the Soviets took a year longer than the Americans to produce a nuclear weapon. Although Soviet scientists were able to use U.S. nuclear diagrams stolen by Soviet spy Klaus Fuchs, they still had to address their own range of scientific and technological challenges unique to the Soviet context. This involved extensive experimental work that they were hoping to avoid by using previously tested designs. In effect, Soviet scientists created their own tacit knowledge while adapting the technology to their own environment. Similarly, the British nuclear program took two years longer than the U.S. program to produce a bomb, even though British scientists had worked directly on and received documents from the Manhattan Project. MacKenzie and Spinardi say this was

because British scientists were not involved in all aspects of the Manhattan Project and lacked important tacit and explicit scientific and technological knowledge. The translation process therefore often leads to a "reinvention" of the technology, because vastly different circumstances at the new location cause the product resulting from the translation to differ from the original.[23]

The local character of knowledge is also expressed in the often inaccessible or hidden idiosyncrasies of a specific laboratory. Those idiosyncrasies cannot be standardized and transferred to a new location because they reflect individual and communal knowledge along with laboratory disciplines and routines not always recognized as part of an experiment. For example, in her analysis of the 2002 synthesis of poliovirus, Kathleen Vogel emphasizes the importance that laboratory personnel placed on respecting certain disciplines and laboratory practices to limit the introduction of uncertainties in an experiment already riddled with unknown variables. The Stony Brook laboratory made sure to maintain "sameness" in the laboratory by using the same technicians for key stages of the experiment, the same equipment, and the same suppliers of material. These practices, developed over decade-long experimentation and testing by laboratory scientists, were shared within the institution, allowing newcomers to benefit from their colleagues' past experience. Although these practices did not guarantee success in the experimental work, they had become important parts of the laboratory culture and a unique feature of that specific laboratory.[24]

In another analysis of laboratory practices, sociologists of science Kathleen Jordan and Michael Lynch emphasized how laboratories develop their own internal dialects and rituals, even though newcomers often do not see the need for them. For example, a common practice in some laboratories is to shut off the overhead lights while working with DNA. Although the reasons for doing so remain unclear to most newcomers, they perpetuate the practice because everyone else does it. Similarly, some researchers re-sterilize previously sterilized equipment before starting an experiment.[25] In the field of missile technology, Charles Draper, the father of missile guidance technology, imposed a certain discipline in his MIT laboratory that extended to nonscientific personnel. He required janitors to report any time they knocked a test table with their broom, and warned those who assembled gyroscopes and accelerometers not to wear facial hair. In Draper's mind, these were important details: a bumped table or a strand of facial hair could cause the sensitive equipment to malfunction.[26] To the casual observer, however, these practices might not appear essential.

Knowledge Production, Transfer, and Learning as a Social Process

Studies in the various disciplinary fields discussed in this chapter indicate that just as the transfer of tacit skills does not imply automatic learning,

learning does not occur in all conditions. Specific factors are required to allow the learning and creative process to proceed. These include the state of knowledge at the starting point, the need to create a common knowledge base, the existence of a work environment allowing informal communications, and the development of trust between collaborators.

One key factor in learning tacit knowledge is the recipient's base knowledge. Individuals absorb new ideas better when they can associate them with things they already know. In other words, building on existing expertise is easier than learning something completely new. Conversely, transferring knowledge from the source to the recipient is easier when both have knowledge in common, which results in part from similar training and backgrounds.[27]

However, building this common knowledge requires more than just formal training. Several studies have shown that informal interactions within and outside an institution are essential for the transfer and learning process to occur. Trading stories at the water cooler, during lunch, or in other informal settings allows individuals to share and acquire knowledge, too. Such informal communications are part of the process of creating a common knowledge based on theoretical and practical experience. Informal communications also help foster a common technical language that allows individuals to better interpret and absorb the ideas of their peers. This process is especially important for novices or beginners who, because of their limited exposure to a field, need to complement their theoretical knowledge with practical expertise. The stories they hear informally from their peers can prove invaluable to novices,[28] widening the personal library of examples they can draw on to analyze and solve new problems.[29]

An interesting study comparing how physicians of various types and levels of expertise solve problems shows that domain experts in specific branches of medicine, such as endocrinology and cardiology, use nonanalytic reasoning to solve medical cases in their domain. In nonanalytic reasoning, rather than analyzing each feature of a case individually, which would take considerable time, experts consider the case as a whole and use a process of "forward reasoning." These experts search for patterns in the medical case under consideration and compare them to the patterns of previous cases to develop a diagnosis faster. To illustrate this point, the authors of the study presented a medical case involving an endocrinology-related disease and asked two groups of physicians to solve the case. The first group was composed of endocrinologists with clinical experience in their domain, while the second group was composed of practicing cardiologists. Not surprisingly, the domain experts analyzed the case faster and proposed a correct diagnosis, while the cardiologists carefully examined each feature of the case, taking longer to propose a diagnosis, which proved to be incorrect.

The authors repeated the experiment, this time using only endocrinology experts. The first group had practitioners with clinical experience, and the second group had researchers with no clinical experience. The two groups were asked to solve two cases, one simple and one more complex. In both cases, the researchers' group took more time than the practitioners to analyze the problem, using an analytical process. Although the researchers solved the simple case correctly, they made an incorrect diagnosis for the more complicated case. The group of practitioners solved both cases correctly. But when asked to explain their reasoning, the practitioners could not always do so, implying that much of their knowledge had become implicit and difficult to verbalize.[30] This study not only illustrates the role that practical and tacit knowledge play in problem solving but also emphasizes the fact that individuals with theoretical knowledge in a field but who lack practical experience and the tacit knowledge that comes with it are at a disadvantage.

Another important factor in tacit knowledge transfer and learning is trust in the idea that positive results can be achieved. In his analysis of the Q of sapphire, Collins showed that much of the Western scientists' inability to reach measurements as high as those of the Soviets during the Cold War was due to their lack of trust that such measurements could be achieved. Only after witnessing a Russian scientist's successful experiment did the British scientists become aware that failure is part of the experimental process—the Russian scientist sometimes failed for no apparent reason—and that the Russian scientist's trust that he could achieve positive results allowed him to persevere until he did so. In other words, scientists need to understand that they will have to endure a certain number of failures before reaching success. By observing a Russian scientist, British scientists learned the time frame required to succeed.[31] The role of trust in biological developments was also underscored in the cases of the cell extract production for the poliovirus synthesis and the "plasmid prep"—a common preparatory procedure in molecular biology—two tasks based on well-known but highly irreproducible methods because they are subject to many contingencies beyond a scientist's control. Similarly, in the case of the "plasmid prep" and the poliovirus synthesis, scientists who observed others' successes were then able to persevere until they, too, succeeded, even if they had to extensively modify the method.[32]

These studies demonstrate that producing, creating, transferring, and learning tacit skills are part of a social process in which individuals learn through exposure to more experienced colleagues—as much as they do through their own experimentation and personal practice. As a result, knowledge is dependent on connections among individuals, their histories, and their physical circumstances, making it context dependent and not always easy to use in different circumstances.

Knowledge Reservoirs

In addition to assuming different forms, knowledge is also stored in various reservoirs. Written documents—be they blueprints, protocols, scientific publications, or other scientific data—are the main reservoirs of explicit knowledge, as they can be easily transferred and stored for long periods of time. Written documents, however, contain only knowledge that can be codified. Much of the knowledge created during experimental work is tacit and cannot be easily captured in written form. In addition, different types of documents serve different purposes and may only contain data useful to their target audience—be it the general public, professionals, or experts in a specific field. For example, scientific articles are notoriously incomplete: their methods section is generally brief, and their main purpose is to show that a concept has been implemented, not to allow replication by others.[33] Such articles are usually intended for a small group of experts in the field, whose experience can help decipher the data and measure the advancement proposed in the article.

Experimental protocols are a second form of explicit data, generally produced by a university laboratory or an industry to accompany a commercial product, such as a kit to perform a certain procedure. Such protocols are also designed for professionals in the field; they are thus more detailed than scientific publications, tending as they must toward helping others replicate a task or method. Still, they, too, can be difficult to use because they constitute a mix of objective scientific data, scientists' personal experience with the procedure, and the idiosyncrasies of a specific laboratory culture. Experimental protocols usually reach another lab through the transfer of a lab researcher who can demonstrate how to use them. Users also typically modify common protocols by introducing shortcuts or fusing different methods. Such modifications are rarely documented and usually transferred orally. Books can describe standardized methods that can be applied to a variety of uses, but because of their general character, books are rarely easily applicable.[34]

These written documents are all incomplete reservoirs of knowledge, which explains why they require extensive interpretation, user modifications, and adaptations to fit specific needs and work conditions.[35] The incomplete nature of documents also stems from the fact that they record knowledge at a specific point in time, whereas knowledge creation and learning are dynamic processes.

In scientific institutions and firms, individuals are the main reservoir of knowledge, acquired through their own direct experience and observations and through collaboration with colleagues. However, in complex projects, individuals are only partial reservoirs of the knowledge pertaining to a technical artifact. Complex products such as weapons systems require

large teams from various disciplines, so any one person's knowledge of the product is limited to his or her own contribution to the larger system. A wider and more complete knowledge of the technical artifact is retained collectively—or shared among teams of scientists and technicians. As a result, the collective has a more accurate understanding not only of the technological artifact itself but also of the reasons why certain technical decisions were made. Because collective knowledge far exceeds the capabilities of any individual, it cannot be centrally stored; instead, it is spread across the organization. Much of this knowledge is also tacit in nature, making its transfer or reproduction difficult without the intervention of the collective.[36]

Another, often overlooked, knowledge reservoir is corporate culture. In their analysis of firms' "organizational memory," management researchers James Walsh and Gerardo Ungson define corporate culture "as a learned way of perceiving, thinking, and feeling about problems that is transmitted to members in the organization. . . . This culture translates in shared language, frameworks, symbols, and stories."[37] Shared culture is the product of past experiences, transmitted to new generations of employees through informal discussions, training, observation, behavior, or explicit rules of conduct. Like tacit knowledge, corporate culture conveys both certain values and scientific practices. Although the details of the experimental context and decisions may be lost over the years, corporate culture allows newcomers to benefit from the experiences of their colleagues and predecessors. However, although corporate culture is a reservoir of tacit knowledge, it is not a good retention mechanism for contextual information: the context of and the reasons for certain technical decisions may be distorted or lost through multiple transmissions over time. Only individuals and the collective can retain contextual information.[38]

Communities of practice are also important reservoirs of knowledge. Unlike corporate culture, which is confined by the walls of an institution, communities of practice embrace a whole professional community. Communications and exchanges between individuals within communities of practice allow methods and approaches to spread. In the process, such exchanges enrich personal and communal knowledge, as well as that of the corporate culture. Scientific institutions generally view scientific exchanges, particularly the circulation of postdoctoral students, as an essential way to gain new knowledge. The example of the postdoc who brought to his new lab a specific way of shaking a test tube, which he learned elsewhere, demonstrates how communities of practice can enrich an institution's knowledge.[39]

A final knowledge reservoir is the organizational structure of an institution. In complex projects, in which different teams perform specific tasks, the organizational structural reflects the sequence of tasks. More precisely, the organizational structure indicates how the specialized knowledge cre-

ated within each division is transferred to and used by other divisions, creating a new institutional knowledge.

Although they contain different types of knowledge, these individual reservoirs are interdependent. For example, though tacit and explicit knowledge are distinct, the boundaries between them are hard to delineate, and the two are intimately connected. For example, the explicit knowledge in diagrams and notes is based in part on information that cannot be captured in writing and therefore requires a certain level of interpretation. Even nuclear weapons codes, generally believed to embody explicit and objective knowledge, require personal judgment to understand because they reflect the designer's experience.[40] In the field of biology, written protocols can be hard to use even by individuals with the appropriate education. Only when protocols are used in the context of the acquisition of motor and other sensorial skills via practical training do they start to make sense to the user. In other words, explicit data needs to be teamed with motor, sensorial, and other tacit skills to acquire meaning.[41] Thus, the absence of tacit knowledge can prevent the use of explicit information and make it difficult to repeat previously successful experiments—even when attempted by experienced individuals.[42]

Similarly, individual knowledge is intertwined with communal knowledge. One person's knowledge and understanding of a technical artifact depends on the knowledge of his colleagues. Without the collective, individual knowledge is spotty, unable to explain all the technical decisions made in developing a scientific artifact. The British nuclear scientists' inability to produce a weapon faster than the United States did—despite having contributed to the Manhattan Project—illustrates this concept. As a result, individual knowledge feeds communal knowledge, and vice versa. Communal and personal knowledge are also fed by the corporate culture and the communities of practice, which—by creating a common technical language, common symbols, and a common knowledge base—allow exchanges, interpretation, and innovations to occur. Without the new blood provided by corporate culture and communities of practice, personal and communal knowledge is more limited and, consequently, less able to address and solve problems that arise during experimental work or production. One can see why the current conception of bioweapons knowledge reduced to written data can result in dramatically erroneous assessments.

Given the interdependence of knowledge reservoirs, it is not surprising that access to information from one but not the others strongly limits the ability to replicate past work. The question is whether limited access simply makes replication more arduous or can prevent it altogether. Stated differently, does the loss of one knowledge reservoir compromise or prevent the use of the knowledge contained in the other reservoirs and possibly lead to the loss of a technology?

Knowledge Loss

Although we have focused thus far on how knowledge is acquired, it is also important to look at how knowledge can be lost. Due to its impact on productivity, performance, and profits, knowledge loss has been an important topic of study in the field of economics. When employees retire or organizations are restructured, mistakes, disruptions in production, or decreases in output quality often follow, due to a loss of know-how.[43] Empirical studies show that interruptions in production are sufficient to trigger knowledge loss that may occur rapidly, even in highly standardized processes that require only low-skilled workers. When the activity is resumed, performance tends to be inferior. This suggests that knowledge needs to be replenished continuously; otherwise, it depreciates.[44] Scholars in the science and technology field have also observed that tacit knowledge can decay over time if it is not used, practiced, or transmitted to a new generation of specialists. Trying to re-create lost knowledge can be difficult, if not impossible.[45]

Knowledge loss can occur at different levels. At the organizational level, a massive loss of personnel due to restructuring or retirements may cause an institution to lose valuable experimental knowledge and insights. For example, when the engineers who designed the Saturn V rocket—used to launch manned missions to the moon—were encouraged to take early retirement in the 1990s, NASA lost much of the knowledge it had developed during the years of moon exploration. In addition, the few individuals at NASA responsible for integrating the rocket's parts, which were produced by various subcontractors, left the space organization, too. As a result, when President George W. Bush announced his Constellation program to send men to the moon, NASA scientists could not use the Saturn V expertise and had to design new rockets from scratch. Tellingly, a Government Accountability Office report found that in 2009, after spending about $10 billion on the Constellation program, NASA was still struggling with a number of technical problems, such as designing a new engine, limiting vibration during launch, and eliminating risks of hitting the launch tower during liftoff—problems former Saturn V engineers and designers had encountered and solved.[46]

Knowledge loss may also occur at the division or unit level when people fail to document modifications in processes or mistakes in engineering designs, leaving newcomers to face insurmountable hurdles. For example, after a worker retired from a Texas Instruments radar system assembly line, problems with the quality-control boards immediately ensued. The company hired an engineering consultant to examine the issue, but the problem could not be solved. The company then decided to recall the retired worker, who immediately pointed to the problem after observing new workers on the line: they were turning a part in the wrong direction. The new workers were actually following the engineering drawings to the letter. But the drawings were incorrect, which the retired employee knew and had cor-

rected in her practice, but had not mentioned to management. The cost of this oversight was $200,000.[47]

Finally, knowledge loss may occur at the individual level, when a person stops practicing an activity. Studies in the field of psychology have shown that implicit—or tacit—knowledge can be retrieved only through the modality that was originally used to store it. If the knowledge was stored visually, it cannot be retrieved using another modality, such as speech.[48] This implies that to retrieve implicit know-how, individuals need to be placed in the same conditions that produced the knowledge in the first place.

The existing literature, however, fails to address two questions fully: Are all knowledge reservoirs equally capable of preventing replication if access to them is denied, or is the loss of specific kinds of knowledge reservoirs more damaging? And what is the rate of knowledge loss in weapons technology? Answers to these questions are important because they allow better estimates of terrorist group or state capabilities to replicate past work, and they permit a firmer understanding of a country's or terrorist's capacity to maintain an existing program or restart a past program.

Several case studies in recent years offer preliminary, if imperfect, answers to these questions. The first involves Fogbank—a nuclear warhead component that the U.S. Department of Energy forgot how to produce. The second revolves around chlorine dispersion, which the U.S. Department of Homeland Security failed to model properly. The third involves the slow loss of knowledge pertaining to nuclear warhead design and testing within the U.S. nuclear weapons complex.

FOGBANK

As part of a program to prolong the operational capability of nuclear warheads by replacing aging parts, the U.S. Department of Energy (DOE) identified in the late 1990s one component of the W76 nuclear warhead that needed replacement. The part, known as Fogbank, is a foam used between the fusion and fission stages of the W76 thermonuclear warhead for the Trident missile. When DOE officials identified the need to produce new batches of the foam in 2000, they realized that the industrial capacity and knowledge required to support production no longer existed. The Oak Ridge, Tennessee, facility that had once produced the warhead, beginning in the 1970s, was dismantled in 1990, and its personnel retired or took other jobs. In addition, no documents on how to produce the foam were retained. Attempts to relearn how to produce the foam faced tremendous technical difficulties, in part because the production involved toxic and flammable material that is difficult to handle safely. This led DOE officials to change course and design an alternative product that could replace the Fogbank. That meant developing new designs, building a new production facility at Oakridge, and training new personnel—all of which cost approximately $70 million and took nine years.[49]

This example is interesting in several respects. First, it demonstrates how quickly knowledge can decay and how much time and expense may be required to produce an alternative solution. In this case, the knowledge loss took place over ten years—between 1990, when the capacity was dismantled, and 2000, when the loss was identified. It took almost as many years to produce an alternative product because the original could not be re-created. Second, the loss of knowledge entailed not only the explicit knowledge related to the production protocols of the Fogbank but also several forms of tacit knowledge. The departure of key individuals resulted in the loss of personal knowledge, skills, and practices along with the communal knowledge embedded in the teams of workers, engineers, and technicians. With the dismantlement of the production plant, the knowledge embedded in the corporate culture and work organization was also lost. Given that the facility was the only one producing the foam, its dismantlement effectively led to the un-invention of a unique technology.

CHLORINE DISPERSION

A second case concerns the modeling of toxic gas dispersion by the U.S. Department of Homeland Security (DHS). In a 2010 press release, DHS acknowledged that its modeling of toxic gas dispersion, based on small-scale releases of chlorine, had proven erroneous. The acknowledgment followed train collisions in Graniteville, South Carolina, in 2005 and in Macdona, Texas, in 2004, during which toxic chemicals, including chlorine, were released. Instead of spreading over a large area, as DHS models predicted, the cloud of chlorine gas remained close to the ground, near the point of impact. In both collisions, people near the point of impact who called 911 were instructed to remain indoors, which actually increased their risk of harm. In both cases, individuals who were closest to the impact and remained on site died—nine victims in Graniteville and three in Macdona. Several hundred others needed medical attention in Graniteville, while forty-three people were hospitalized due to chlorine inhalation in Macdona. To correct the erroneous advice in case of future chlorine accidents or voluntary releases by terrorists, DHS announced that it would contract for a study to better understand toxic chemical dispersal patterns. The study would start by identifying the lessons learned from the two train collisions, based on a meeting of railway experts, chemical industry representatives, and the public safety teams that responded to the accidents.[50]

During World War I, German and French troops used chlorine gas extensively as a chemical weapon. Both countries filled cylinders with the toxic agent and waited for favorable wind conditions before releasing it toward the enemy. Even then, they knew that without the proper weather conditions, the gas would linger above the ground.[51] Chlorine was also part of

the U.S. chemical weapons arsenal, and readily accessible U.S. Army archives chronicle the development and testing of chlorine.[52]

Nonetheless, DHS officials did not seem to be familiar with this information. It may have had something to do with the demise of the U.S. chemical warfare program since the nation signed the Chemical Weapons Convention (CWC) in 1993. This treaty bans the development and use of chemical weapons and requires the destruction of existing arsenals. Consequently, the individuals who had knowledge of these weapons have left the Army and may not be easy to locate or consult. It is also possible that as a result of the CWC, the Army's knowledge of gas behavior on the battlefield has largely disappeared, and only knowledge of its behavior during destruction remains essential. Because the DHS is a relatively new organization, created after 2001 to deal with domestic emergencies, it is also possible that its personnel did not make the appropriate contacts with the Army to discover where the knowledge of chemical weapons resides or resided. In this case, although the explicit knowledge about chlorine dispersion still exists, the knowledge was actually lost for DHS personnel because they did not have access to another knowledge reservoir: individuals with expertise in chlorine dispersion. As a result, they, too, had to reinvent the knowledge by commissioning a contractor to do so.

U.S. NUCLEAR WEAPONS COMPLEX

A third example of knowledge loss is occurring within the U.S. nuclear weapons program. Concerns about knowledge loss in the nuclear complex have preoccupied laboratory personnel and management since the early 1990s.[53] With the breakup of the Soviet Union and the end of the Cold War, the emphasis turned to arms reduction, not further nuclear weapons development. There followed a moratorium on nuclear testing, and negotiations to sign the Nuclear Test Ban Treaty. As a result, U.S. nuclear laboratories have not designed, produced, or tested nuclear weapons for about two decades. Laboratory restructurings and reorganizations since the mid-1990s have also led to an important loss of personnel, through downsizing or retirement. For example, 2,600 out of the 9,400 employees at Lawrence Livermore National Laboratory have been laid off.[54] Sandia National Laboratories has lost at least 5,000 employees since 1993 to downsizing and voluntary departures, and the laboratory was scheduled to lay off a few hundred more in 2012 to reach a total downsizing of 10 percent for the year.[55] The scientific culture of the laboratories has also been greatly modified, in part due to a redirection of the laboratories' activities away from weapons development and toward other scientific endeavors, including the maintenance and repair of existing nuclear weapons.[56] Moreover, the introduction of a new for-profit management that focuses less on scientific developments

and more on security issues has also contributed to nuclear-knowledge loss.[57]

Taken together, these changes have had a profound impact on the various knowledge reservoirs that constitute the nuclear complex. Personnel downsizing affects communal knowledge and the communities of practice that were formed at the laboratories during fifty years of nuclear weapons development. The design and testing of nuclear weapons brought together a varied group of individuals, including physicists, chemists, engineers, technicians, and explosives specialists, who created an identity around the task of transforming a physics principle into a complex working weapon.[58] Their knowledge was passed on from one generation to another through formal training, informal communication, practice, apprenticeship, and gradual inclusion of novices into this community of practice. Testing of nuclear weapons created a common knowledge in the form of explicit data, but also tacit practices and values.[59]

This communal knowledge started to erode with the departure of individuals who contributed to nuclear weapons design, production, and testing. In 2000, an estimated half of the designers with relevant experience at Los Alamos were in their mid-fifties and expected to retire by 2005.[60] The diagnostics group, which developed sensors that were placed near the explosion to collect data, saw most of its members retire between 1996 and 2000.[61] Those who remain have their own personal knowledge, but due to the complexity of the nuclear enterprise, no individual fully understands all the details of nuclear weapons design, development, production, and testing. Thus, a portion of the communal knowledge has already eroded, and it is unlikely that it can be re-created. Due to the lack of practice, personal knowledge may have also suffered. Importantly, it is difficult to measure the loss without an actual attempt at re-creating what individuals once produced.

The corporate culture has also been deeply affected not only by these changes but also by the discovery of several security breaches at Los Alamos in 1999 and through 2003. These led to dramatic changes in laboratory management, which deeply affected scientific work. From a laboratory managed by scientists who had risen through the ranks and enjoyed their peers' respect, Los Alamos was transformed into an organization regulated by strict security rules and rigid managers drawn from the military and private industry, who alienated the scientific staff by emphasizing tighter security rules over scientific achievements. Similar managerial changes and priorities were instituted at Lawrence Livermore National Laboratory. This generated numerous conflicts between lab personnel and new managers, leading many senior scientists to depart and scientific output to decrease. As a result, personnel were not motivated or encouraged to nurture and transfer the values and know-how they had developed over the years.[62]

The knowledge embedded in the organizational structure was also affected by these changes. The absence of nuclear weapons development damaged

the links between functional teams within the laboratories, who now had less reason to cooperate or communicate with each other.

As a result, the nuclear complex is leaking knowledge from all reservoirs. Certainly, the leak is a slow one. Explicit data is still available in the form of blueprints and other scientific documents. Some of the personnel who participated in the design, production, and testing of nuclear weapons are still at the labs. Beginning in the 1990s, the national laboratories also launched programs to preserve data and make it easily retrievable, including memories of those who contributed to weapons development and testing.[63] Old-timers with practical experience in designing, producing, or testing nuclear weapons have started tutoring new recruits, handing off skills and tricks that cannot be transferred through formal training or documents. Nonetheless, this knowledge can only be spotty at best. A physicist who headed the design group at Los Alamos between 1978 and 1981 noted that written documents and designs are incomplete representations of the work they conducted. Many of the changes were made on the fly, before testing. Much of the work done under deadline pressure was not recorded. Some drawings were not updated. The tutoring program instituted at Los Alamos can only transfer a portion of the original scientists' knowledge. The real test of the new recruits' understanding must come through the production and testing of an actual nuclear weapon—something they are not allowed to do. Testing can only be done through computer modeling, which may not accurately simulate weapons' behavior. In the past, for example, some designs worked a couple of times and failed other times, without obvious reasons. It is unlikely that computer models could simulate such uncertainties.[64]

WHAT RESERVOIRS MATTER MOST?

The three examples just discussed provide not only a useful illustration of the interdependencies among knowledge reservoirs but also a better understanding of which reservoirs, were they substantially degraded, might lead to a loss of knowledge that could trigger the un-invention of a technology.

The Fogbank example illustrates a case in which all reservoirs of knowledge were lost, making replication impossible, even within the same program. A new product had to be designed to replace the lost technology. In the other two cases, the reservoirs of explicit knowledge have been preserved, but different factors hamper their use. In the chlorine dispersion case, the potential users did not know the data existed or could be retrieved, making it effectively lost to the new generation. Thus, the absence of mechanisms to transfer past expertise allowed the knowledge to erode. In the nuclear weapons complex, the data are available and new efforts were made to gather additional tacit information to facilitate their use. Yet empirical studies show that passing written or oral instructions to someone for use in actual practice is not an easy process.

This analysis shows that reservoirs of tacit knowledge are essential not only to replicating past work but also to preserving a technology. Indeed, the erosion of tacit knowledge through lack of practice, reorganization, or restructuring that affects corporate culture, work organization, routines, and communities of practice can have a deleterious effect on a technology, as demonstrated by the case of the Saturn V rocket, as well as the Fogbank and the chlorine dispersion examples.[65] So it is not surprising that the U.S. nuclear weapons complex has attempted to maintain tacit knowledge reservoirs by recording the memories of old-timers and encouraging them to mentor a new generation of designers and developers. Yet these attempts might not be as successful as desired, because some tacit knowledge will always escape codification. Critically essential expertise can only be acquired through practice.

The political science and policy literature is filled with assertions that knowledge and science-based technology are universal, independent of context, impersonal, public, and cumulative. This view suggests that science can be expressed in "perfect language," is broadly accessible and understandable, and is therefore easy to master and replicate. We have seen why that is not true.[66] Scientific knowledge is in fact local, person specific, private, and noncumulative. Because tacit knowledge is transmitted from person to person and contained in various reservoirs, there are greater barriers to the spread of expertise than the traditional view might suggest. Thus, the likelihood that an untrained individual with minimal theoretical knowledge could produce a biological weapon, as former secretary of state Clinton asserted in her 2011 Geneva speech, is very slim.

CHAPTER 3

Impediments and Facilitators of Bioweapons Development

The challenges of knowledge creation, transfer, and use, and the interdependence of knowledge reservoirs, discussed in chapter 2, raise two important questions: How can a program create the appropriate conditions to ensure efficient knowledge use? And, what conditions might prevent success? Understanding what factors impede or facilitate knowledge acquisition and successful use has rarely been the focus of extant policy and political science literature.[1] This lacuna is due to the assumption that success requires nothing more than assembling adequate scientific and engineering talent and providing the equipment they need. Testimonies from former bioweapons scientists and historical accounts of past bioweapons programs show the profound shortcomings of this belief. Soviet bioweapons scientist Igor Domaradskij writes in his memoir that the Soviet bioweapons program essentially failed to produce the new generation of bioweapons it set out to develop in the 1970s despite a prodigious investment in human, material, and financial resources.[2] The U.S. bioweapons program also was largely unable to produce a weapon that met military requirements, while more recent state and terrorist programs have failed at various or all stages of bioweapons development in spite of having access to the material and financial resources.

This should not surprise us. Given the fragility and unpredictability of bio-agents, and the challenges of tacit knowledge creation and institutionalization, the environment required to achieve fruitful interactions does not occur spontaneously; it must be engineered in an especially appropriate organizational context. How bioweapons programs organize the succession of stages of a weapon's life cycle, ensure their interface, synchronize tasks, and manage human interactions necessarily affects scientific results. Organizational and managerial factors thus constitute key determinants of success because they have a direct impact on knowledge creation and transfer within a program. Evidence from past state and terrorist bioweapons programs also underscores the importance of four additional factors that affect successful

systems integration: political support or intrusion, the overall program's economic circumstances, program location, and the type and timing of foreign technical assistance. Since programs face a unique set of circumstances, their results will necessarily vary. Similarly, the circumstances of each facility within a program may also vary, which can result in differing degrees of success within the same program. To underscore the stiff barriers facing bioweapons development, particularly operating under covert conditions, this chapter explores the organizational and managerial requirements of knowledge creation and institutionalization, and examines the effects of exogenous factors on scientific results.

Organizational Requirements of Knowledge Creation and Institutionalization

In complex technical projects, where the work performed by specialized individuals, teams, and divisions depends critically on the extent to which it is shared broadly across the organization, specific mechanisms must be deployed to allow coordination and sharing among the various knowledge reservoirs. Without such mechanisms, knowledge becomes fragmented and trapped within the walls of each reservoir.[3] The extant literature has identified two key organizational factors that promote the efficient use and transfer of knowledge: first, a structural organization that ensures personnel proximity and mobility; and second, the deployment of integrative mechanisms that ensure the coordination and synchronization of tasks and stages.

STRUCTURAL ORGANIZATION: PERSONNEL PROXIMITY AND MOBILITY

Given that the acquisition and use of tacit skills and know-how requires direct interactions between people, often over a prolonged period of time, proximity between individuals and mobility within their organization are essential vehicles for knowledge transfer. This is especially true in bioweapons programs, which must deal with unpredictable microorganisms, novel problems, and complex uncertainties, all of which demand close and frequent collaboration and coordination between diverse technical staff.

A large body of literature suggests that the best way to foster a direct exchange of information among individuals and teams is to ensure personnel proximity.[4] For example, the field of economics has long noted the importance of proximity in its study of "industrial districts." Industrial districts are clusters of specialized entities operating in the same field of activity, with complementary skills and knowledge. The high-tech companies populating Silicon Valley south of San Francisco and the biotechnology companies located in and around Boston typify the industrial district phenomenon. In

these districts, knowledge transfer occurs through two different channels. First, institutional collaboration promotes knowledge spillover as companies learn from one another through their common projects. Second, because of their geographic proximity, workers within industrial districts have numerous opportunities to meet professionally or socially and exchange information. Moreover, workers in industrial districts are generally highly specialized and skilled, which creates frequent opportunities to move from one company to another within the district. In doing so, they introduce new practices, ideas, and tacit skills that may spark innovative approaches at their new workplace. In Silicon Valley, for example, several innovations and new companies can be traced directly to the movement of personnel within the district.[5]

The importance of proximity and co-location in knowledge transfer is also displayed in the natural sciences field. Research conducted by Isaac Kohane and other scientists at Harvard Medical School indicates that physical proximity of researchers strongly correlates with the research impact. The study analyzed 35,000 articles published in 2,000 peer-reviewed journals by 200,000 life scientists from Harvard Medical School between 1998 and 2003. It assessed the impact of the published research by mapping the precise location of coauthors and counting the number of subsequent citations. When coauthors were located in the same building, their papers were cited considerably more often than those produced by authors located in different buildings or locations. In general, the number of citations decreased as the distance between authors increased. These results were true whether the papers had two authors or dozens of authors. According to Kohane, these findings suggest that physical proximity promotes the exchange of ideas, resulting in more fruitful collaboration and higher quality work. They also reinforce the importance of designing architecture and facilities that support frequent physical interactions.[6]

Proximity therefore plays a crucial role in creating connections between different reservoirs of knowledge and enriching their component parts. It fosters communities of practice, in which direct communications between members serve as conduits for the transmission of values, practices, and certain ways of doing things.[7] Proximity also promotes the likelihood of unplanned interactions between people, which can improve coordination between functions within an organization.[8] At the individual level, proximity allows greater feedback: when workers can routinely discuss processes or ideas with colleagues, they are better able to identify failure points and adjust rapidly.[9] Conversely, distance impairs the transfer of knowledge, because it limits opportunities for knowledge spillover through informal and serendipitous interactions between individuals.[10] In the defense field, for example, several reports published in the 1980s indicated that the organizational separation and distance between U.S. Department of Defense laboratories inhibited technology transfer.[11]

It is worth noting that Soviet authorities had recognized the importance of proximity for knowledge transfer. When, in the early 1970s, they launched a vast expansion of the bioweapons program, they placed some of the new bioweapons facilities close to existing scientific centers. For example, they built the State Research Center of Virology and Biotechnology (known as Vector) in Koltsovo, about thirty miles from the scientific city of Novosibirsk—Akademgorodok in Russian—to facilitate the transfer of current knowledge of biology to support the work at the new bioweapons research institute. Akademgorodok included research centers specializing in physics, chemistry, and biology, notably the Siberian branch of the Academy of Sciences and Novosibirsk State University, which provided much of Vector's personnel.[12]

Another key requirement of knowledge transfer is personnel mobility. Allowing people to move between divisions, or from one location to another, can not only reinforce the benefits of proximity but also compensate for the lack of physical proximity. Personnel mobility is indeed the most effective way of transferring and using knowledge within and between facilities for two different reasons. First, as noted earlier, technologies or processes do not transfer easily, because they do not contain the tacit knowledge that helped create them in the first place. When technologies travel with the people who contributed to their design, they are more readily adapted to the new site. These individuals have the ability not only to bring the tacit knowledge associated with the technology but also to adapt and restructure their own knowledge so that it meshes with the infrastructure and knowledge base at the new location. They may even modify the receiving environment to better accommodate the technology.[13] Second, personnel mobility allows staff throughout an organization to understand who in the organization is proficient in particular skill sets. By moving around the facility's divisions and working with people outside their own group, individuals create a personal directory of expertise among their colleagues that they can draw on when needed. Without such a directory, the knowledge available within an organization becomes less accessible to the whole staff, slowing down or complicating scientific breakthroughs. Economists call this shared knowledge of existing expertise within an organization "transactive memory" and have shown that it improves coordination and allows people to work more effectively together. Even when assignments are unclear, people can leverage their colleagues' expertise to solve problems they face.[14]

INTEGRATIVE MECHANISMS

Although personnel proximity and mobility facilitate knowledge transfer by allowing direct and serendipitous interactions between people, they do not automatically engender a spontaneous coordination of stages. This is particularly so in complex projects such as bioweapons programs, in

which stages are highly interdependent—the execution of one stage is dependent on the successful completion of the previous one—and each stage involves distinct teams representing different disciplines. Thus, the results of one team's work may not mesh in time and specification with those of another team. The successful development of a working weapon also requires the deployment of at least two specific coordinating mechanisms. First, lateral linkages between stages must be established to coordinate interdependent tasks, so that knowledge created at one stage can be transferred to and used effectively during the next stage. Second, a systems integration process that synchronizes all the stages of a project is needed to remove bottlenecks and solve problems before they become too large to handle and induce failures.

Lateral Linkages. In the bioweapons field, the importance of stage coordination is illustrated by the challenge of scaling up fragile biological organisms. Schematically, the development of a bioweapon proceeds through five main stages. First, during the research phase, teams of scientists and laboratory personnel who specialize in bacteria, viruses, or toxins study and develop an agent with appropriate characteristics (virulence, antibiotic resistance, pathogenicity) for weapons use. Then another team that specializes in production process development takes over the sample to design ways to produce the agent in slightly larger quantities while maintaining all the agent's desirable qualities. The product is then moved to the production phase, where engineers and technicians test the production process by producing small quantities of the agent in a pilot plant. The objective here is to identify potential problems that might prevent a further scale-up to industrial quantities. In the fourth stage, animal experts test the resulting product on primates or other laboratory animals to model its effects and determine whether it can produce the expected results on humans. The last stage, weaponization, is executed by engineers, explosives experts, mathematicians, and statisticians who design delivery mechanisms and test the dispersion of the agent in a specific weapon delivery system. Although in theory these stages occur sequentially, in practice, the evolution from laboratory sample to manufactured product is never a linear process. The viability of fragile organisms requires numerous changes in key parameters such as temperature, type of reagent, or time required for reactions to occur and to maintain their characteristics as the product moves along the production process. Depending on their intrinsic characteristics, biological agents also react differently to scale-up, which means there is no one best way to scale up successfully.[15] The passage from one stage of product development to the next requires a constant back-and-forth between stages and direct interaction among participants.[16] This is not easily achieved when the programs include hundreds or even thousands of individuals located at different sites.

Empirical studies in economics and management have shown that improved coordination of stages can be achieved by deploying specific tools that foster lateral linkages between people and facilitate the passage from one stage of a project to the next. A particularly successful lateral coordination mechanism used in industry is called functional overlap. This entails creating linkages between key stages of a product's life cycle. For example, production plant engineers might be involved in the upstream stage of product design to assist their colleagues in making design decisions that will facilitate production. Functional overlap has been shown to have a positive impact not only on the quality of the final product but also on knowledge use within an institution. By allowing individuals from a downstream stage to contribute to decision making in an upstream stage, and vice versa, this mechanism allows the institution to limit the sources of uncertainty and reduce costly errors that may occur downstream. It also introduces a greater level of flexibility in product development in that modifications to a product can be made throughout the project's life cycle, in real time, instead of waiting for the final integrative stage. When functions are spread out geographically among different facilities, as is the case in most big science and weapons projects, functional overlap may involve personnel rotations between facilities or the temporary placement of teams of personnel in another facility to help solve problems.[17]

Functional overlap is especially important when an organization must adapt to new technologies. Studies have shown that difficulties in introducing new technology can lead to productivity losses equal to or greater than the cost of the new technology and create disruptions that can last for two years or more. However, there is a strong positive correlation between the number of linkages employed between functions and the speed with which new technology is effectively incorporated and subsequently translated into improved productivity.[18] Other lateral coordination strategies used in industry include creating interdisciplinary teams to solve unexpected problems; forming transition teams, which follow a product to its next stages in order to solve unforeseen difficulties; and appointing liaison officers, whose goal is to connect various parts of an organization.[19]

Because it is built into the work organization, lateral coordination is a form of planned personnel mobility that reinforces the benefits of proximity and co-location. Lateral coordination can also compensate for a lack of proximity. When stages of a product's evolution are located at different sites, the existence of lateral coordination mechanisms between sites can promote teamwork and create transactive knowledge because they allow more frequent interaction between disparate parts of an organization or a project, thus allowing personnel to create directories of knowledge available throughout the program that they can tap into when needed. Lateral coordination between sites can also promote—throughout an entire program—efficient use of technical expertise, cross-fertilization of knowledge, collective problem

solving, and an ample supply of communal knowledge. Lateral coordination also has an important effect on the organization of a project: it helps break down hierarchical and structural divisions and bring decision making closer to the sources of information, making individuals more engaged in various parts of a product's life cycle, and allowing an organization to respond more easily to uncertainty.[20]

In the pharmaceutical industry, in which the passage from one stage of product development to the next poses similar challenges to those in the bioweapons field, scale-up problems are common, and the coordination of upstream and downstream stages and people is viewed as one of the best ways to avoid disaster. Indeed, the inability to achieve reliable scale-up has at times led to abandoning the production of what seemed to be promising drugs.[21] In the bioweapons field, Soviet authorities decided against creating lateral linkages within their bioweapons program to limit individual knowledge of the program. This caused many scale-up nightmares, as demonstrated by the difficulties of producing the Soviet anthrax weapon. Although the technology was new for the Stepnogorsk scientists, Stepnogorsk and the institute that originally developed the weapon in small quantities did not institute knowledge transition mechanisms or functional overlap procedures. In addition, at the time, most Stepnogorsk scientists had no experience with bioweapons or with large-scale production, which led to several years of delay in rectifying start-up problems.[22] Scale-up difficulties were also encountered in the production of the Soviet smallpox weapon. When the Vector facility was tasked in 1986 with the development of a large-scale manufacturing process for smallpox, its personnel had no experience with such activities. Recognizing the problem early on, Vector's director was able to intervene with Moscow authorities and bring in two scientists from the military Center of Virology at Zagorsk to help with the new technology development. Zagorsk, which was built in the 1940s, had much experience growing smallpox using the traditional method of cultivating the virus in chicken eggs, and also had pioneered a production process using small-scale bioreactors.[23] The two military experts who joined the Vector team were able to train their colleagues and allowed them access to production protocols written by Zagorsk scientists. It nevertheless required four years for Vector and Zagorsk scientists to come up with a formulation that could withstand the stiff requirements of scale-up, and the quantities produced with this new method were still lower than those obtained with the traditional chicken egg method. One of the handicaps Vector scientists faced was that they were civilians, and the Zagorsk protocols were guarded by the KGB and restricted to military scientists. Only by specific request from the Zagorsk scientists were the protocols made available to Vector personnel—on a need-to-know-basis only.[24] This example illustrates the difficulties in transferring knowledge to those who need it in the absence of lateral connections between stages. It also illustrates the problems caused by the absence of a

complex-wide integrative mechanism that permits the work performed in one part of the program to benefit another part. Such an integrative mechanism is called systems integration or systems engineering.

Systems Engineering. Because large and complex projects are composed of many moving parts, integrating these parts into a coherent whole—a process known as systems engineering—is particularly challenging and affects a project's success or failure. Not surprisingly, the importance of systems engineering emerged around the same time as big science, in the few years leading up to World War II (WWII).[25] Many of the WWII technological and military projects involved participants from universities, industry, and the military, each performing distinct portions of a project that needed to be integrated together. For example, the U.S. bioweapons program involved seventy-eight universities and almost two hundred private companies performing various research or production activities for the program.[26] Such large projects gave birth to the concept of "systems engineering," defined by one of its creators, missile systems developer Simon Ramo, as "the discipline of the design of the whole, to realize a harmonious and effective ensemble, as distinct from the design of the parts."[27] In other words, systems engineers are individuals who see a project through, from its inception to its end, and synchronize and align the work of the different participants. Thus, they contribute not only to the development of the project concept but also to its design, research and development, and execution. But instead of focusing on the execution of each individual part and task, systems engineers focus their attention on the connection points and interfaces, so individual parts mesh with each other throughout a program and produce a working technical artifact. Whereas WWII systems engineers were deeply involved in specific projects and honed their skills through their experience in these projects, postwar systems engineers were a cadre of individuals working in companies specializing in systems engineering, and trained to assess from the outset whether a project was technologically feasible and attainable within the budgetary and time constraints imposed. To that end, systems engineers had to not only be proficient in several technical disciplines relevant to the project but also possess appropriate managerial skills, allowing them to solve engineering problems as well as deal with the diverse disciplines and constituencies involved in the project.[28]

The integrative role of systems engineers is vital to the success of a project, and no amount of money can compensate for their absence. In the United States, for example, a decreasing number of young graduates have entered the field of defense-related systems engineering since the end of the Cold War, leading to the multiplication of cost overruns, delays in project execution, and technical failures in military projects.[29] A recent review of several military projects sponsored by the National Academy of Sciences and the National Academy of Engineering showed that deficient systems engineer-

ing skills caused the development of satellite systems that did not work. One system, designed to detect foreign missile launches, included two types of sensors that interfered with each other: one sensor emitted electromagnetic interference that disabled the other, preventing their simultaneous use. In another case, the Pentagon started building a complex network of communication satellites without having developed a coherent plan to integrate them.[30]

In the bioweapons field, systems engineering skills are essential in ensuring the development of an agent that can be scaled up, mass produced, and weaponized. Within the U.S. bioweapons program, Fort Detrick had among its staff four individuals who were formally responsible for synchronizing the work of Fort Detrick personnel with that of the Pine Bluff and Dugway sites—the other two main facilities of the program. Although they were formally called "liaison officers," they performed the tasks typically handled by systems engineers.[31] These individuals were typically heads of production divisions, with specialized experience in different categories of agents. For example, one of them had a degree in microbiology and biochemistry. He then managed the virus pilot plant, became chief of the Agent Process Branch, and later was appointed head of the Product Development Division. In these various positions, he conducted research and production activities related not only to viruses but also to bacteria and rickettsiae.[32] In contrast, the Soviet bioweapons program elected not to include a systems engineering function. Although some individuals were responsible for integrating portions of weapons projects executed by different institutes, their role was limited to assembling the disparate parts. They did not have responsibility for managing the whole project, overseeing execution by the diverse participants, or solving bottlenecks that may have occurred at one stage or at a participating facility. These responsibilities were assumed by individual institute directors or laboratory heads, and only for their portion of the project. As a result, problems with a project were often discovered at a late stage, leading to delays and failures.[33]

Managing Weapons Programs

Although organizational factors are essential in allowing knowledge transfer between divisions and facilities, they do not guarantee that personnel in the recipient unit will accept and use that knowledge. As discussed in the next section, studies have indeed shown that new knowledge is sometimes rejected due to trust issues or lack of common technical language. Managers have an important role to play in ensuring acceptance and use of new knowledge, and their influence manifests itself in three important areas. First, they are essential in establishing a social context that promotes trust and cognitive cohesion—the creation of a common technical language—among

personnel, which increases the chances that personnel will accept and effectively use their colleagues' knowledge. Second, they play a particularly important role in creating the proper environment for knowledge institutionalization. By creating a corporate culture that promotes openness and learning, managers ensure not only that technical knowledge is widely shared and sustained over time, for long-term use, but also that knowledge of problems and bottlenecks that can affect a program can reach decision makers for swift adjustment. Finally, managers are essential conduits for allowing sustained communications between political decision makers and program implementers, to ensure continued political and financial support for the program.

SOCIAL CONTEXT, TRUST, AND COGNITIVE COHESION

Complex projects such as weapons programs rely on heterogeneous groups of individuals with different competencies, who frame and approach problems differently. This creates cognitive boundaries and trust issues that are difficult to overcome, making the knowledge created by one unit not readily usable by another unit. Weapons programs also must contend with cultural differences between military and civilian personnel, who operate according to different cultural and administrative rules. Work on a common project therefore requires the creation of a common technical language that will allow diverse technical communities to collaborate, learn from, and trust one another, lest they become veritable Towers of Babel.[34] Such levels of trust and cognitive cohesion, however, are difficult to achieve without the intervention of program managers, even when proper organizational mechanisms are in place to ensure the transfer of knowledge.

For example, studies in the field of economics suggest that personnel mobility does not automatically generate acceptance of new knowledge by the receiving party. Visiting personnel are sometimes not as well trusted as resident members of a team, thus limiting their influence at the recipient site. A study measuring knowledge transfer during temporary rotations of personnel found that the recipient institution/group used ideas generated by visiting individuals less frequently than it used ideas generated by resident members. However, both resident members and visitors created more unique ideas after the visitor returned to his institution than they did before or during the exchange.[35] This suggests that a cross-pollination of knowledge occurred during the exchange but materialized in new ideas only in environments where individuals trusted one another and could translate the acquired knowledge into a language that group members could understand and use.

Other studies have shown that changes in team membership can be harmful for a team's performance if the skills of the new member do not mesh well with those of the other team members. In addition, the new knowledge may not be used because it might entail modifying existing relationships or routines, potentially involving a reorganization, which groups often resist.[36]

Other studies have emphasized the role of technological-path dependency in limiting knowledge transfer through personnel mobility. A firm on a specific technological trajectory may be less likely to welcome new knowledge from someone outside the company. This is especially true for groups that work in the firm's core competencies, because new ways of doing things often require substantial changes in organization or approach.[37] This implies that the transfer of knowledge is more likely to succeed in a new organization, where routines and work organizations are fluid, or when the new knowledge is acquired in a noncore competency. On the other hand, knowledge transfer is hard in an established organization unless it has specific mechanisms to ensure that new members and their knowledge are integrated.[38]

The Soviet bioweapons program provides an apt illustration of these phenomena. In 1986, by order of central authorities in Moscow, a scientist from the Vector research institute was sent to a sister facility in Obolensk, both in Russia, to help solve technical problems in combining the causative agent of plague with the diphtheria toxin in a biological weapon. Although the Vector scientist had useful expertise, he met tremendous resistance at Obolensk. Deputy directors of the Obolensk facility viewed the visiting scientist as a threat to their own positions. Indeed, some thought he was sent to replace them because of their lack of progress, which caused numerous conflicts. Even Obolensk's director perceived the visiting scientist as an outsider imposed on him by Moscow, which led to his reluctant provision of help gathering the personnel, space, and material required for the visitor's research. Staff members reassigned to the visiting scientist's group also showed no inclination to contribute. The visiting scientist had to manufacture a variety of incentives to motivate his new colleagues, one of which was to dispense ethanol alcohol. Communist party leader Mikhail Gorbachev's efforts to fight alcoholism in the late 1980s had made consumable alcohol scarce and expensive, so Russians were using ethanol from science labs as a substitute for vodka and even as currency. This gave the visiting scientist some leverage to reward good behavior or punish dissent among his new colleagues. But because the Obolensk institute had been in existence since 1974 and was populated mostly with military personnel who had developed their own idiosyncratic ways of doing things, which clashed with the desired new approaches, it took the visiting scientist three years to set up a laboratory within Obolensk. Although he achieved some promising results by 1989, it took another two years before he was supervising a well-functioning laboratory able to achieve significant results. Altogether, it took five years to achieve Moscow's directive.[39] This example illustrates the critical importance of managerial support to allow formal mechanisms of knowledge transfer to achieve their full potential.

Extant economics and management literature suggests that managers can help establish trust and erase boundaries between people and disciplines by creating a social context that promotes exchanges and cooperation, which in turn helps establish cognitive cohesion throughout a program.

Several studies have shown that informal ties created through socialization lead individuals to create friendships that increase their willingness to share information and help each other. The stronger the ties between individuals, the more time and effort they are willing to invest in providing assistance to each other and transferring their knowledge. Friendship and frequent communications also play an important role in the development of trust, an essential ingredient in knowledge sharing and use. The provider can trust that the information shared will not be appropriated by the recipient for his or her own interests, while the recipient has increased confidence in the source's competence, thus increasing the chances that the received knowledge will be accepted and used. Studies have also shown that the trust and access created by friendship increase the likelihood that individuals will seek help when faced with technical challenges, because the cost of reciprocity and the reputational risk associated with admitting ignorance are much reduced.[40]

Socialization also contributes to the establishment of cognitive cohesion by increasing the frequency of interactions and improving the quality of communication. People who interact frequently communicate more effectively by fostering a common language and shared concepts that allow improved mutual understanding. Social ties are also important conduits for the transfer of values and behaviors within an organization and within larger communities of practice; they also enable the spread of shared understanding and interpretations that contribute to improved communications.[41]

KNOWLEDGE INSTITUTIONALIZATION

The role of managers is also particularly important in creating the proper environment for knowledge institutionalization. In order for an institution to make progress and to innovate, it must ensure that knowledge acquired by an individual or a group can spread across the organization. This not only allows others to benefit from that knowledge but also permits the whole organization to adapt to new knowledge by, for example, adopting new routines or modifying existing production processes. Several studies have shown that the institutionalization of knowledge requires specific managerial interventions.

One key element of knowledge institutionalization is the creation of baseline conditions to allow organizational learning. Organizations learn by modifying organizational norms or practices to absorb new knowledge created by individuals and teams. This occurs first by embracing error and promoting double-loop learning, which involves not only finding solutions to errors but also identifying their underlying causes and taking appropriate action. Typically, when errors occur, individuals and teams tend to learn in single loops: they try to correct failures by implementing technical solutions or modifying their strategies without questioning the underlying

cause of the failure. Underlying causes can be embedded in organizational norms or policies, or in organization-wide practices that prevent investigating the cause, or exist by virtue of individuals' own assumptions. For example, when delays in production occur, single-loop learning would involve trying either to modify the production process or to acquire new technology to eliminate delays. On the other hand, double-loop learning would question whether the setting of the production time frame is actually appropriate and take action to modify organizational goals or decision frameworks, if necessary. To ensure double-loop learning, organizations need to allow individuals and teams to address the underlying causes of failure in a safe, open environment, without fear of embarrassment or reprisals.[42]

Managers can promote organizational learning by creating a corporate culture that promotes openness and rewards information sharing. One strategy for creating such an environment involves implementing a shared vision of what should be accomplished. Some companies organize meetings to discuss management strategy, and collect comments and views from staff members. These consultations allow personnel to voice their concerns or anticipate potential future problems, which may lead to changing strategies or deciding to set up checkpoints to revisit a strategy should it show signs of failure. This way, personnel feel more involved in decision making and become more committed to the overall vision—even if they disagree with a decision. The ability to discuss potential failure points in advance and establish a review system also allows employees and management to acknowledge errors more easily, thereby reducing concerns that individuals might be personally blamed for future failures. Such interactions also lead to establishing more realistic goals and limiting the stress and pressure that come with the inability to meet targets.[43]

Motivation and incentives are also important facets of organizational learning. When personal achievements are recognized and compensated, individuals have greater incentives to do good work. If individuals are motivated only by self-interest, however, power games and politics can foster conflicts and competition among people or units, preventing the use and spread of new knowledge or fostering sloppy work. For example, a study of research conducted in the field of physics showed that in the 1960s, the pressure of competition and the requirement to publish for peer recognition was already having detrimental effects on scientific work. First, the fear that colleagues or competitors might take credit for one's work if shared too openly led many scientists to adopt an opportunistic approach, withholding information instead of sharing data for the common good. Second, pressures to produce and publish for career advancement reduced incentives to conduct long-term and deep research in which scientists take the time to develop, test, and verify theories or ideas, and possibly to cooperate with colleagues to acquire new insights before publishing. Instead, a new trend started to emerge that favored conducting fast and superficial

research and publishing it before significant results were achieved, to imprint one's mark on an idea or just advertise ongoing work.[44] Similar trends were noted in biology and medicine in the past few decades. Competition and the pressure to publish sometimes led researchers to fabricate or manipulate data, to plagiarize, or simply to produce bad science.[45]

In the U.S. and Soviet bioweapons programs, there was very little pressure to publish because of the secrecy of the work. Within the U.S. program, this led to a decrease in competition and a greater level of cooperation. But such cooperation evolved only because managers had established a review mechanism to prevent personnel from taking credit for their colleagues' achievements.[46] No such cooperation existed within the Soviet system, and cases of stolen research and findings were not uncommon. For example, a young scientist working at the Vector research institute witnessed the laboratory director use her findings to write an article without giving the scientist the credit she deserved.[47]

Conversely, the emphasis on negative incentives, in the form of punitive actions for errors, can lead to avoidance strategies, preventing the identification of problems and their resolution. A study dealing with near-miss accidents in the airline industry, for example, found that the potential for punitive action was associated with lower levels of lesson drawing and performance improvements by crew members.[48] In the bioweapons field, sanctions for failure were stiff in the Soviet and Iraqi programs as well as in the Japanese terrorist group Aum Shinrikyo, leading personnel to report fake results or even fabricate data to please higher-ups and avoid punishment.

Openness to the outside world is another means of enhancing organizational learning. When companies and scientific organizations have finite resources and rely on a determined set of competencies, they can get trapped in familiar ways of doing things, which limits their development. For example, scholars have noted that industrial districts that become closed to outside ideas tend to fail. The leather industrial district in Italy, having become a leader in the field, came to distrust developments produced outside its realm, eventually risking its future prospects.[49] Managers who promote openness to the outside world effectively allow their workforce to access a more diverse pool of knowledge and larger communities of practice, which can improve productivity or scientific results.[50] Bringing in new blood via postdoctoral fellows, scientific exchanges, or collaborations with other institutions is one strategy often used to allow the acquisition of external knowledge.

Finally, nurturing openness and an environment where people can safely identify problems and search for solutions also requires communication channels that easily pass information up and down the hierarchy.[51] This permits knowledge created at various work levels to spread across the entire institution, if needed.[52] This also helps capture critical knowledge that could be lost due to highly skilled worker retirements or departures, and avoid costly and time-consuming consequences.[53]

The inability of an organization to institutionalize knowledge can lead to loss of knowledge and decreased performance, and can even have tragic consequences.[54] For example, in their book analyzing the *Challenger* and *Columbia* shuttle accidents that occurred in 1986 and 2003, respectively, Julianne Mahler and Maureen Casamayou show that the accidents were attributable not only to engineering and hardware problems, but also to organizational and managerial shortcomings that stifled institutional learning about past errors. NASA had a fragmented structure in which its various centers competed rather than cooperated, raising barriers to information flow between the organization and its contractors. It was also fraught with communication problems. Warnings of technical flaws identified by experienced engineers in advance of the shuttle launches were not conveyed to the relevant decision makers, or the decision makers refused to take them seriously. In some cases, pressure applied at higher decision levels led to retractions of previous failure warnings. The organization also developed a culture that discouraged open discussion of problems; employees felt stigmatized if they raised alarms. In addition, pressure to meet launch targets led many managers at various decision points to ignore or gloss over identified technical issues, accumulating errors along the way. In short, NASA's inability to create an organization capable of learning and institutionalizing knowledge was a major contributor to the two accidents.[55]

Achieving proper conditions for knowledge institutionalization in weapons programs is particularly challenging because they are subject to secrecy requirements, which translates into restricted access to information through compartmentalization. In many cases, too, weapons programs are placed under military control, which tends to favor strict vertical hierarchies, centralized decision making, and bureaucratic rigidity—conditions that are poles apart from the required openness and flexibility needed for knowledge institutionalization. The challenges are even steeper in illicit bioweapons programs launched or maintained after the signature of the Biological Weapons Convention, because maintaining absolute covertness places greater demands on management, making the creation and transfer of knowledge problematic.

VERTICAL AND HORIZONTAL COMMUNICATIONS

In his analysis of the Draper Laboratories—the birthplace of missile guidance systems—Donald MacKenzie introduced the concept of the "heterogeneous engineer," an individual who manages and sustains the alliances that will provide support for a long-term technological project. This concept was based on the role of laboratory head Charles Stark Draper in bringing together heterogeneous groups of individuals to support the development of missile guidance systems, thus ensuring the enduring political and financial sustenance of his project.[56]

Regarding weapons development, the role of a heterogeneous engineer is critical in two ways. Because weapons programs can suffer from the uncoordinated actions of the various political and governmental actors involved in setting funding and goals, it is important to realign these actors around what makes sense for the program. By sustaining support for a program, the heterogeneous engineer therefore serves as a communication link between decision makers at the highest level and helps them rally around a specific goal. Equally important, the heterogeneous engineer serves as a link between political decision makers and program implementers by explaining to the higher levels the problems facing the program, the goals scientists can and cannot achieve, and possible solutions to roadblocks. To do so, however, the heterogeneous engineer must be in tune with program implementers to represent them realistically. Charles Draper possessed an extraordinary knowledge of guidance technology, including having developed the theory and invented much of the inertial navigation technology that improved the operational effectiveness of aircraft, submarines, and space vehicles.

Still, the heterogeneous engineer need not have invented the technology to enable a better alignment between overall goal setting and implementation. For the Manhattan Project, General Groves, who was an engineer but did not contribute to the scientific work within the nuclear program, effectively served as the spokesman for the nuclear weapons program in Washington. Although the program had high priority, its ever-increasing needs for funding, personnel, and material resources required continuous justification from government and congressional representatives. This demanded that Groves provide government representatives proof or assurances that the program was making progress and would soon deliver a weapon. General Grove's peripatetic schedule permitted him to stay in close touch with the disparate parts of the Manhattan Project as well as his Washington superiors.[57] In contrast, the U.S. bioweapons program did not have a heterogeneous engineer who could relay field realities to the government agencies involved, and help sort out their respective demands and schedules. Thus, the program lacked focus and suffered from tepid funding and programmatic indirection.[58]

Exogenous Factors

Whereas organization and management affect a program's outcome because they influence how knowledge is created, used, and transferred within a program, several external factors can also affect scientific outcomes because they can interfere with the stability of the work environment, the continuity of scientific work, and the integration of its constituting parts. Stability in the work environment is essential for ensuring the proper use and transfer of knowledge and allowing personnel to accumulate knowl-

edge over time. Interviews with former U.S. and Soviet bioweapons scientists disclose that teams of scientists must work together for an extended, uninterrupted period of time to assimilate the acquired knowledge, learn from one another, and create new collective knowledge to make progress on weapons development.[59] Perturbations in the work environment can set back the clock in an experiment and slow progress down because they frequently lead to knowledge loss, particularly when the interruption is long lasting. In past bioweapons programs, four exogenous factors have conspired to upset a program's stability, continuity, and integration: (1) the level of political priority and intrusion in a program, sometimes teamed with a lack of cohesion in decision making; (2) the economic circumstances of a program; (3) the location of a program; and (4) inappropriate or untimely foreign technical assistance.

PROGRAM PRIORITY, POLITICAL INTRUSION, AND DECISION MAKING

In *Achieving Nuclear Ambitions*, Jacques Hymans argues that when political elites interfere with scientific decisions, program delays and failures occur. On the other hand, when scientists are given the opportunity to develop a professional culture, with minimum interference from political leaders, program success is more likely. This is an important insight that has thus far been ignored by the extant policy and political science literature, and has proven true in many cases, notably the Iraqi nuclear weapons program that Hymans analyzes in his book, and the Iraqi, Soviet, and Aum Shinrikyo biological weapons programs examined in this book. In these three cases, interference took the form of goal setting that was out of sync with what scientists could actually do; placement and replacement of scientists based on political loyalty rather than competence; and interference with the natural flow of scientific discovery, requiring scientists to skip essential phases to reach the requested result faster. In all three cases, such intrusions resulted in multiple disruptions in scientific work, the emergence of questionable scientific behaviors—faking or fabricating results—in some cases due to the creation of a cadre of incompetent scientists; and a loss of knowledge, which eventually negatively affected these programs' paces and outcomes. Hymans's argument, however, does not explain why program failures occur even when political elites adopt the required laissez-faire approach. For example, why is it that the U.S. bioweapons program failed to produce bioweapons deemed appropriate for the battlefield even when the political elite did not directly interfere with the scientific work? Similarly, why was the South African bioweapons program unable to produce a weapon, achieving only the development of poisonous substances for assassination purposes, even though the scientific director was given carte blanche in terms of programmatic decisions and budget use?

Answering these questions requires examining other aspects of political elites' involvement in a weapons program. Specifically, it requires looking not only at the interactions of government elites with scientists but also at the interactions *between* government elites. Typically, several government agencies and military services are involved in decision making for a program. These actors often have different and sometimes conflicting views about a program's goals and priorities. Reconciling these diverging views can be a daunting task, particularly when funding decisions are not centralized. For example, within the U.S. bioweapons program, conflicts and disagreements appeared at the very first stage, while the program was being set up. Ira Baldwin, who was hired to establish the program in 1943, noted in 1967: "I soon began to learn that there were wheels within wheels in the Chemical Warfare Service, and not everybody agreed on everything that came up."[60] About a dozen agencies were involved in decision making for the U.S. bioweapons program. Such dispersion of responsibility and decision making not only nurtured conflicts and disagreements about the program's objectives but also negatively affected the program's direction and scientific output.[61]

Although the Manhattan Project was also subject to conflicts and tensions among political and military leaders, it still produced a working weapon in a remarkably short period of time. To be sure, the program was impelled by the necessities of war. Yet however seemingly prosaic, the nuclear program benefited from the sustained and direct actions of General Groves—the program's heterogeneous engineer—who was able to reconcile divergent views and objectives, and influence decision making to provide direction and support for the program.[62] Although the American biological weapons program had many supporters and detractors, archival data do not point to the existence of a sustained and vocal heterogeneous engineer within the U.S. political and military establishments. In addition, although the program was placed under the administrative oversight of the Army Chemical Corps, programmatic and budgetary decisions remained scattered among several agencies throughout the program's life span, resulting in fluctuating budgets. In short, the bioweapons program suffered from low priority within the political and military establishments, even more so after the advent of nuclear weapons, and the lack of a heterogeneous engineer to streamline programmatic and budget decisions.[63]

Laissez-faire can also be taken too far with respect to oversight and political support. In South Africa, for example, political and military establishments entrusted all decision making for the bioweapons program to its scientific director, Wouter Basson, and limited their role to signing off on budget requests. This complete lack of oversight meant that Basson could capitalize on the program's high priority and high level of secrecy to divert much of its funding for personal use and replace competent scientists with loyal friends lacking the proper expertise, all the while lying to his superiors about the program's achievements.

The U.S. and South African examples show that in order to evaluate more accurately the influence of political and military elites on weapons development, one needs to identify what agencies are involved in goal setting and funding decisions, how they coordinate their respective objectives, what level of priority they give to the program, and whether these factors translate into sustained political and funding support, as well as mindful oversight of the program. Absent these conditions, disruptions and instability are more likely to prevail.

ECONOMIC CIRCUMSTANCES

Economic circumstances in which a bioweapons program operates are rarely taken into account when evaluating the level and speed of its achievements. This omission is due to the common assumption that political authorities will always find ways to steer the required resources toward programs they deem important, even under trying circumstances. This is particularly the case in authoritarian regimes, where economic decisions are made centrally. Yet even in highly centralized systems, such as the Soviet Union's central-planning system, decision making and economic reality do not always coincide. In the Soviet context, the centralization of economic decisions and the deficiencies of central planning had a palpable effect on scientific achievements and on how science was accomplished, especially in the bioweapons program.

In spite of receiving high political and funding priority, the Soviet bioweapons program faced the same challenges as the rest of Soviet industry due to the inability of central planners to coordinate supply and demand, making the distribution of goods and materials slow and often unsuitable to regional needs.[64] In the bioweapons complex, this meant frequent shortages in research materials, such as nutrient media and equipment, which not only interrupted scientific work but also pulled scientists away from their experiments to solve procurement problems. Often, scientists had to allocate a portion of their time to the on-site production of equipment and materials that could not be obtained through normal state supply channels.[65] Moreover, competition for scarce resources produced power struggles among agencies, facilities, and scientists, who had to rely on an intricate network of connections at the regional, national, and federal levels to enhance their chances of obtaining the necessary resources.[66] According to former Soviet bioweapons scientists, these power struggles often generated conflicts among personnel or management and at times resulted in a loss of knowledge: scientists who became too powerful or challenged authority were replaced or sent to another facility.[67]

The Soviet economic system also had a direct impact on scientific behaviors and practices within the bioweapons complex. Like other economic or defense-related activities, the Soviet bioweapons program was subject to a

five-year plan, in which Soviet authorities in Moscow defined the overall objectives for the bioweapons complex. Frequently, these objectives were unrealistic because they were defined by individuals who either had no scientific expertise or had been away from practicing their skills and had lost touch with what could realistically be achieved. This created tensions between planning authorities and implementing agencies, which trickled down to the facility level, generating unfavorable work conditions and questionable behaviors. For example, after the Obolensk facility received orders in the early 1980s to develop a tularemia strain that was at once highly virulent, antibiotic resistant, and vaccine resistant, the facility director and the project's lead scientist clashed frequently over the lack of progress. Although nobody really knew how to achieve Moscow's stiff goal, failure to implement the plan bore severe consequences, ranging from decreased supplies for the duration of the five-year plan to the removal of the facility's management. Consequently, no attempts were made to modify the project's objectives or time frame, which eventually led to the project's termination in the late 1980s.[68] In addition, because bench scientists had only limited opportunities to influence the five-year plans, they often resorted to faking results or fabricating data.[69] These behaviors were allowed to continue because secrecy and system fragmentation reduced higher authorities' ability to identify the source of dishonest results. Sometimes these authorities even condoned such behavior, because they, too, risked sanction when those under their authority performed inadequately.[70]

By allowing little or no involvement of subordinate levels in decision making, centralization can create disconnects between planning authorities and implementing agencies and facilities, resulting in ill-defined or unattainable objectives. In the case of the Soviet program, the negative effects of centralized decision making were reinforced by the features of the Soviet planned economy, most notably its inability to ensure adequate supply of required material. This created delays and disrupted the progress of scientific work, making it even more difficult for the complex to achieve its set goals.

LOCATION AND VARYING PROPERTIES OF MATERIALS

The location of a program also becomes an important factor affecting program success or failure. Several studies have shown that location is important because the properties of the materials, equipment, or parts necessary for scientific work may differ from one location to another. Variable properties can negatively affect replication of past work and the transfer of technologies to a new site, ultimately complicating integration of parts and stages.[71]

In his analysis of laser developments, Harry Collins discusses the case of a physicist who, having worked on laser developments in his previous laboratory, set out to build a replication of the previously used laser at his new

location. Despite the fact that the physicist had contributed to the design and development of the original laser, had access to equipment from that laboratory, and received assistance from former colleagues, his attempted replication failed. Collins explains this lack of success by emphasizing the absence of a complete set of tacit knowledge, as well as the challenges associated with the transfer of technology discussed in previous chapters. He also emphasizes the role of the varying characteristics of the parts used in the new laboratory. For example, after comparing parts of his machine with those used in his former laboratory, the physicist observed that the capacitor leads used in the original machine were much shorter than the ones used in his new machine. The challenge was to determine how short they should be, as existing protocols required that the leads be as short as possible, and no specific measurement was provided. By modifying the design to introduce shorter capacitor leads, the physicist also observed that other parts, such as the glass tubes used in his machine, were too large or not flat enough and needed alterations. These modifications, however, did not immediately lead to a working machine. Additional testing and consultations with former colleagues were needed to achieve success. Interestingly, after successfully completing this replication (replica 1), the physicist decided to build another copy (replica 2), this time by using smaller parts. Not surprisingly, his attempts were unsuccessful. Although each new part worked properly when tested on replica 1, they did not operate when installed in replica 2. Collins concludes that components that appear to have the right specifications may not work, particularly if they are used in new ways, as was the case in replica 2.[72] This example also underscores the importance of location as a determinant of part specifications. Minute changes in material or component characteristics, due to the use of different suppliers at a new location, can prevent successful integration and derail an experiment.

The role of location and the properties of materials used in scientific work are nowhere more important than in the biological sciences, where scientists work with live agents that are unpredictably sensitive to environmental conditions. For example, the properties of reagents and other materials used in scientific experiments may differ from one location to another and frequently vary seasonally. An experiment conducted successfully in one location may not be reproducible in another because of the varying properties of the materials used, even when the same individual conducts the experiment. In her analysis of the poliovirus synthesis experiment conducted by virologists at the State University of New York at Stony Brook in 2002, Kathleen Vogel shows that seasonal variations in the properties of the bovine serum used in the experiment had a direct impact on the reproducibility of the synthesis in the laboratory. Differences in water pH affected the replication of the experiment at different locations, even when the work was done by scientists who were previously successful in conducting the experiment. As a result, a team member who had spent six years learning

the technique at the original laboratory was unable to replicate his work in his new laboratory due to, among other things, the different properties of several ingredients at the new location.[73]

A similar example can be found in the biodefense field. A team of virologists at the U.S. Army Medical Research Institute of Infectious Diseases (USAMRIID)—the premier biodefense research facility under the Department of Defense—has tried for several years to replicate a 2001 experiment by a team composed of Russian and German scientists. The Russian-German experiment aimed to better understand the role of a protein in the pathogenicity of the Ebola virus.[74] By manipulating the protein's genetic makeup, the researchers were able to create a mutant that was significantly more cytotoxic than the wild-type virus, thus showing that the studied protein had a direct influence on the virus's pathogenicity.[75] Although a description of the experiment was published in *Science*, USAMRIID's attempts at replicating the work were unsuccessful. A couple reasons have been advanced to explain this failure: (1) USAMRIID scientists did not have the skills of the original team, which happened to include several former bioweapons scientists from the Russian institute Vector; and (2) USAMRIID scientists may have been using methods that were more advanced than those used in the original experiment, and replicating the experiment using old-fashioned methods was not possible because the required material was no longer available.[76]

Within the U.S. bioweapons program, similar reproducibility challenges were encountered when production was moved from Fort Detrick to the production plant at Pine Bluff. First was the challenge of scaling-up pathogenic agents from a pilot quantity of 660 gallons at Fort Detrick to a concoction of 50,000 gallons at Pine Bluff, which required several modifications to the production parameters, such as additives and growth media. Then came the even more daunting task of achieving a contaminant-free slurry at Pine Bluff. Although all equipment and growth media were sterilized, and Fort Detrick personnel made a point to send contaminant-free samples to Pine Bluff, some batches produced at Pine Bluff were nonetheless contaminated with foreign bacteria for no apparent reason. A former Fort Detrick laboratory technician, who often went to Pine Bluff to help scale-up production of the tularemia agent, noted: "It is very easy to contaminate a tank of growing bacteria. . . . It just happens. You have to keep everything sterile, and you have to have a complete contaminant-free sample to inject into your culture[, but] there's always a chance that something, one single cell, is contaminated and grows into millions, billions actually. . . . [The contamination problem] has never been solved."[77] Contamination of biological batches is also a common problem in the pharmaceutical industry. When the biotech company Genentech tested the safety of its first human growth hormone on a group of employees, the recipients fell sick due to the presence of a bacterial contaminant in the drug.[78] Thus, the impact of location on a program's advancement is also important to consider in the context of foreign technical

assistance, in which the use of materials, equipment, and knowledge from different sources may further complicate integration efforts.

IMPORTANCE AND LIMITS OF FOREIGN TECHNICAL ASSISTANCE

Foreign technical assistance is generally viewed as a facilitator of program advancement because it is believed that the provision of technology, materials, or expertise from more advanced countries can propel a nascent program to a higher level. Yet there is a budding literature in the political science field that questions this belief, demonstrating that foreign technical assistance has at times been an impediment in nuclear weapons progress.[79] In view of previous developments emphasizing the challenges of knowledge transfer and the difficult adaptation of technologies and material to a new site, these counterintuitive results underscore paying more attention to this phenomenon. However, what is missing in the recent literature is an explanation of *why* foreign technical assistance has at times resulted in fruitful results while at others has prevented progress.

Appreciating the uneven results of foreign technical assistance on weapons development does not mean that foreign assistance is unimportant. Indeed, it is a central feature of eventual success. All programs have thus far had to elicit the help of friendly countries simply because the breadth of resources required to bring a program to fruition usually far exceeds the capabilities of an individual state.[80] Even the two superpowers during the Cold War could not claim that their nuclear and biological weapons programs were fully endogenous. For example, the U.S. bioweapons program was originally fed by the results of research and testing undertaken by Great Britain and Canada, which had ongoing bioweapons programs long before the United States established its own.[81] Scientific cooperation and exchanges between the three countries continued during WWII and throughout the Cold War, until President Nixon terminated the U.S. bioweapons program in 1969.[82] German scientists also reportedly contributed to work related to gaseous sterilization at Fort Detrick after WWII,[83] and Japanese bioweapons scientists were extensively debriefed by U.S. officials after the war, and provided reports about their human testing.[84]

Much of the equipment and some of the laboratory materials used in the Soviet bioweapons program were of U.S. and European origins.[85] The Soviet Union also benefited from the acquisition after WWII of German industrial techniques and manufacturing equipment for large-scale production.[86] It also gained knowledge about the effects of some pathogens on humans by debriefing captured Japanese bioweapons scientists who had conducted human testing before the war.[87] Many smaller-state and terrorist bioweapons programs extensively relied on foreign assistance in the form of equipment and material procurement, information sources, and education of their scientists and technicians.

Still, to properly evaluate the role of foreign assistance in helping a program make progress, one needs to understand how the assistance provided fits into the existing knowledge and industrial bases of the recipient program. Does the type and timing of the technical assistance coincide with the absorptive and integrative capacity of the recipients—that is, the extent to which they can absorb new knowledge and integrate the disparate pieces of equipment and data obtained from outside sources into a coherent whole? We have seen in previous chapters that when technology or documents are transferred to another program, their use is made very difficult due to the challenges of adapting them to the new environment, particularly when the recipient program has no access to the scientists or technicians who possess the associated tacit knowledge, or if it uses material and equipment having varying properties. Further complications arise when the recipient program does not have a sufficient knowledge base to absorb the data and the technology. Illustrations of this idea can be found in the nuclear and biological fields.

For example, although the British nuclear program had access to documents produced under the U.S. nuclear program, and about two dozen British scientists directly contributed to the American program, Britain encountered significant problems in using data produced under the Manhattan Project. One reason for these difficulties stemmed from the fact that under the U.S. program, British scientists did not contribute to all aspects of bomb design and manufacturing. This left them filling holes, requiring arduous and time-consuming experimentations and research. Even aspects of the program in which British scientists were directly involved, such as the explosive lens design, presented challenging problems that required additional research and testing. Decisions made regarding the assembly and use of the weapon (in-flight as opposed to on the ground, as in the U.S. program) led to alterations in the original design, requiring more research and design work.[88] Eventually, the British program successfully produced a weapon, albeit not as quickly as the United States, because they had the ability to study, interpret, and test the data they obtained. Britain also possessed a workforce capable of understanding what they did and didn't fully grasp and what to do about it. In other words, the British program had a sufficient absorptive capacity to use the data derived from the U.S. program and translate it to their own circumstances.

In contrast, Libya's absorptive and integrative capacity was nonexistent, making the seemingly extensive support received from the covert nuclear supply network founded by Pakistan's A. Q. Khan impossible to use. Starting in the late 1990s, Khan's assistance to Libya had the ambitious goal of providing Libya with centrifuges, uranium hexafluoride, technical information, training, a bomb design, as well as assistance in establishing a local production facility for centrifuge parts. A key obstacle to the fruitful use of Khan's assistance was that Libya did not have a nuclear industry or any

weapons expertise. Therefore, any use of the provided technology would have required the creation of local knowledge and industrial bases, which would have required decades if ever to complete. Libya's deficiencies on the knowledge front became apparent when a group of Libyans were sent to Dubai to receive training in centrifuge production techniques from Urs Tinner, one of Khan's Swiss acolytes. The training failed due to the Libyans' inability to master the operation of complex precision machine tools, which also compromised their ability to produce centrifuge parts with strict tolerances.[89] In addition, much of the equipment the Khan network provided was defective or incomplete, and the bomb designs included information in Chinese, which the Libyans would have had difficulty interpreting without access to the Chinese authors.[90] In short, unlike in the British case, Khan's assistance to Libya was provided too early—before the country had established industrial and knowledge bases capable of handling and interpreting the data and equipment supplied to them. The country had no absorptive capacity and thus little to no capacity to use and test the technology, most of which was found unpacked by international inspectors in December 2003, after Libya renounced weapons of mass destruction (WMD).

Similarly, the Iraqi nuclear and bioweapons programs displayed a very low absorptive and integrative capacity at the outset. Iraq obtained nuclear equipment, materials, centrifuge designs, and production protocols to manufacture uranium enrichment centrifuges from European suppliers—primarily Germany, but also Great Britain, France, Switzerland, and the United States. Iraq's existing suppliers suggested sources of supply; they also shopped around for individuals and companies susceptible to bribery or willing to look the other way. Although this method ensured a certain degree of discretion from suppliers, it did not necessarily result in acquiring the best equipment for their plans. Difficulties in integrating disparate parts were obvious in Iraq's attempts to produce centrifuges based on an illegally acquired design originally developed by the German manufacturer MAN in the 1970s. Some parts were simply defective; others, originating from different sources, could not be easily assembled into a working machine. Another challenge entailed translating the manufacturing and specification drawings of the German centrifuge model into an engineering process that would allow the production of multiple centrifuges and their parts in Iraq. Despite receiving part samples and technical support from their German suppliers, the Iraqis failed several times. Only after three years of intensive work were they able to produce a working prototype.[91] In addition, although Iraq's German suppliers did seem to have practical expertise to help solve problems in their respective narrow fields, their knowledge was insufficient to support the large-scale production of centrifuges. For example, when the Iraqis were faced with technical challenges, the German advisers offered solutions that, instead of solving the particular problem, prompted the Iraqis to adopt a different, more sophisticated, and, inevitably, more

challenging process. Pursuing such a path caused delays and integration challenges.[92] Consequently, much of the equipment illicitly acquired during that time frame to support future production was later found unused by International Atomic Energy Agency inspectors.[93]

In the bioweapons field, Iraq had an equally limited absorptive and integrative capacity. In spite of having almost unimpeded access to microorganisms, laboratory supplies, and equipment from U.S. and European suppliers for almost two decades,[94] efficient use of this technology was negatively affected by Iraq's limited knowledge base. Iraq's scientific community had been depleted since the 1970s due to a policy that rewarded political loyalty over competence. Many competent scientists were jailed or replaced with people who were loyal to the regime and, in some cases, with people who owed their degrees to their political connections. So when the program was restarted in the 1980s, Iraq lacked expertise in key areas of weapons development, such as fermentation, drying, and weaponization. As a result, several years of exploratory work were needed to identify the agents most adapted for bioweapons development. In addition, the program had only one fermentation expert, and before his involvement in the program, the fermentors obtained illicitly remained unused. Similarly, in spite of having access to drying equipment, the Iraqis were only able to produce bio-agents in liquid form.

Consequently, evaluating the role of foreign assistance in weapons development requires digging deeply into the context within which it is offered. Practically, this requires asking two important questions. First, what is the recipient program's absorptive and integrative capacity? Second, do the timing and nature of the assistance coincide with the recipient's absorptive capacity? If a recipient program does not have sufficient knowledge and industrial bases to use, adapt, and integrate the received assistance into their own circumstances, it is likely that the assistance will, at the very least, remain unused, or it may effectively delay and possibly impede progress altogether.

Two related conclusions flow from the developments discussed thus far. First, the endogenous (organization and management) and exogenous variables discussed in this chapter affect scientific work in different ways. Whereas organization and management directly affect knowledge creation and use within a program, exogenous variables affect scientific progress from the outside by either disrupting or supporting the continuity and stability of scientific work. Yet it would be a mistake to attribute to these individual variables positive or negative values and restrict the analysis of a weapons program to measuring their individual effects on the program. The variables are indeed interconnected and affect one another. Although an organizational model that promotes lateral connections and integration of teams and stages is required to ensure the efficient use of knowledge and successful passage from one stage to the next, organization alone cannot produce

the expected scientific results. The intervention of managers, who create a trusting and cooperative work environment, is necessary to allow organizational mechanisms of knowledge transfer to work as intended. Similarly, organizational and managerial factors need to be supported by exogenous variables that ensure the stability and continuity of scientific work. Proper financial and political support and oversight, along with stable economic conditions, reduce the sources of disruptions in scientific work, allowing teams to accumulate knowledge more easily and make faster progress. Economic stability and political support can also help a program more effectively cope with the inevitable challenges of adjusting to varying properties of materials and equipment, and integrating foreign technical assistance into the recipient's knowledge and industrial bases. Therefore, it is important not only to measure the individual effects of each variable on a program but, more importantly, to evaluate how they interact with one another, either reinforcing or mitigating their respective effects.

Therefore, a weapons program should be viewed as an integrated system: it requires specific and essential parts that work individually, but these parts also need to operate when assembled as a whole. Here lies one of the key shortcomings of current threat assessments. Currently, emphasis is placed on only a few variables—material resources—at the expense of other essential ones. In addition, analysis tends to be based on the inventory of individual parts rather than on how they operate together. This shortcoming is particularly damaging in bioweapons threat assessments: due to the fundamental unpredictability of bio-agents and the resulting increased need for integration of teams and stages, bioweapons programs are especially sensitive to the variables that negatively affect integration. This may account for the limited successes achieved in both large- and small-scale bioweapons programs, as will be discussed in the next three chapters.

CHAPTER 4

The American Bioweapons Program

Struggling with a Split Personality Disorder

After almost three decades of operation, President Richard Nixon unilaterally terminated the U.S. bioweapons program in 1969. Most studies explain the program's termination by focusing on the weight of outside political and social pressure, and on the program's inability to produce weapons that met military requirements. Notably, U.S. political and military elites alike were dismayed by how this program was burdened not only by moral concerns but also by uncertainties about the predictability of weapon effects and reliability. These circumstances prevented the development of a use doctrine for these weapons and fostered growing social opposition to biological and chemical weapons during the Vietnam War. Although several biological agents were developed and standardized, only a handful of bombs and spray tanks were developed to carry them. No bioweapons-specific missiles were designed, and biological weapons were never fully integrated into military war plans.[1] Yet the program made some scientific breakthroughs and substantially contributed to civilian science. Very few studies, however, have tried to understand this paradox: Why was it able on the one hand to make progress on the research and development front, but unable on the other hand to produce an operational weapon?

Analyzing the program through the lens of organizational, managerial, and exogenous variables helps shed light on these paradoxical results. The U.S. program is indeed an interesting example of the interplay of positive endogenous variables and negative exogenous variables and their difficult integration. One the one hand, the program adopted an organizational and managerial model well suited to ensure knowledge creation, use, and institutionalization, emphasizing personnel proximity, openness, and system integration, which resulted in numerous scientific innovations. The program's progress, however, was demonstrably delayed by the weight of exogenous variables. The low priority that the political and military establishments gave to biological weapons, and the program's subordination to

several government agencies, led to an unfocused program with fluctuating funding, and an insufficient research, production, and testing infrastructure to meet military requests. In addition, user agencies were out of sync with the actual status of the program due to the lack of a heterogeneous engineer to ensure proper communication between scientists and political and military decision makers.[2] These variables created numerous disruptions in the scientific work at the facility level, leading to an extended knowledge accumulation phase and delayed weaponization. Thus, the positive effects of endogenous variables were greatly dampened by the negative effects of exogenous variables. The net result of this combination of factors is a program that seemed to be struggling with a split personality disorder: coordinated and integrated at the scientific level, while unfocused and discordant at the highest governmental level. This last feature is particularly important to underscore: the lack of coordination at the highest level was essential to preventing the transition from bench science to weaponization—a feature worth exploiting in future nonproliferation policies.

Program Overview

The United States first began its offensive bioweapons program in 1943, although feasibility studies had started two years earlier within the Chemical Warfare Service. This work was expanded in 1942 with the creation of the War Research Service (WRS), which, after receiving a budget of $200,000, enlisted about twenty-eight universities to conduct additional research.[3] Actual offensive work, however, did not commence until the fall of 1943, when construction of the first research buildings at Fort Detrick—the program's central facility—was completed. These included several laboratories, one pilot plant, troop housing, and administrative buildings.[4] In comparison to the U.S. nuclear weapons program, the bioweapons program remained a small enterprise throughout its lifetime. During WWII, whereas the Manhattan Project received a total budget of $2.2 billion and employed 125,000 people at about thirty facilities, the U.S. bioweapons program's budget was $60 million, while its total lifetime budget was approximately $700 million. During WWII the program's workforce comprised approximately 4,500 employees working at two facilities: Fort Detrick, Maryland, comprising research and pilot production; and a testing facility at Dugway Proving Ground, Utah.[5] Additional bioweapons sites were established during WWII, but they did not significantly contribute to the program. One of these sites was the testing facility at Horn Island in Pascagoula, Mississippi, which was activated in October 1943. The facility was closed soon after, however, due to unfavorable wind conditions vis-à-vis the mainland, only ten miles away. Another facility, the Vigo plant, was established at Terre Haute, Indiana, for large-scale production and bomb filling. However, construction and testing

of the facility lasted until the end of the war, in part due to contamination problems during test runs with simulants. The plant was never activated for bioweapons work and was sold to the Pfizer pharmaceutical company in 1946.[6]

Starting in the 1950s, the bioweapons program's infrastructure at Fort Detrick was steadily extended to include several new laboratories, pilot plants, and a one-million-liter spherical test chamber—known as the 8-ball. In 1954, a large seven-story bacterial production plant was established at the Pine Bluff Arsenal in Arkansas; and in 1962, an additional test site was launched at the Fort Douglas Deseret Center in Utah, which merged with the Dugway Proving Ground in 1968.[7] Thus, by the end of its lifetime in 1969, the program was only slightly larger than it was during WWII, with three main facilities instead of two—Fort Detrick, Pine Bluff, and Dugway Proving Ground—and approximately the same number of employees as during WWII.

Under the program, the United States produced a variety of antihuman, anti-plant, and anti-animal agents. Research initially focused on botulinum toxin and anthrax. Work on botulinum toxin, however, gradually decreased, because the agent did not spread easily and would lose some of its toxicity when aerosolized.[8] Throughout its lifetime, the overall program studied about two dozen lethal and incapacitating agents, including the causative agents of tularemia, brucellosis, plague, smallpox, Q fever, and Venezuelan equine encephalitis. It is generally believed that weaponization within the U.S. bioweapons program centered on agents for which countermeasures were available or could be developed to protect the troops, and that although contagious diseases such as plague and smallpox were studied, they were not weaponized.[9] However, a recently released list of technical reports[10] about testing activities at Fort Detrick's 8-ball and at Dugway Proving Ground shows that several tests with dried *Variola*—the causative agent of smallpox—were conducted to investigate the dispersion and decay of aerosolized preparations.[11] Additional tests were conducted with *Variola*-filled E25 warheads for the Honest John rocket.[12] Anti-animal research originally took place at Fort Detrick, but when expansion of the work required additional space, a dedicated facility was established at Camp Terry on Plum Island, New York. The Plum Island facility was transferred to the Department of Agriculture, and animal work was terminated at Fort Detrick in 1954.[13] In addition to weapons-related work, the Central Intelligence Agency's Special Operations Division at Fort Detrick conducted research on the use of biological agents for covert operations, including assassination.[14]

Fort Detrick scientists also pursued a defensive line of work, consisting of research on developing new types of personnel protection (masks and other high-containment apparel), decontamination solutions and procedures, and medical countermeasures (vaccines and other therapies).[15] By necessity, Fort Detrick also created a Medical and Safety Division, which, due to the

novelty of bioweapons research at the time, was essentially designed from scratch. However, these nascent biosafety developments became the foundation for today's widely used biosafety practices. Examples include the creation of specialized glove boxes, negative air pressure, sterilization, and incineration systems.[16]

To test agents and weapons designed at Fort Detrick, scientists conducted a variety of indoor and open-air experiments. Animal testing in the 8-ball test chamber typically involved primates used as models to extrapolate the minimum lethal dose for humans. Open-air trials of simulants and pathogens were conducted in field and offshore tests, as well as through the use of special operations units to release simulants in urban areas and metropolitan transit systems.[17] Such open-air tests simulated the dispersion of lethal and incapacitating agents in several different environments: at sea, to evaluate the vulnerability of ships; in urban areas, to assess transport system vulnerability; in cities, to model the spread of pathogens through air-handling systems; and in the arctic, to test the performance of infectious aerosols in extremely cold conditions, such as regions of Russia and China.[18] Although some human testing occurred sporadically before the 1950s, systematic studies on humans were started only in 1954, with Project White Coat. The project enlisted conscientious objectors from the Seventh-Day Adventist Church, who volunteered to test aerosolized incapacitating agents such as Q fever (coxiella burnetii) and tularemia, which can be fatal but for which a vaccine was available.[19]

Hence, until the 1950s, work within the bioweapons program consisted primarily of studying various agents; developing culturing, production, and drying methods; and experimenting with various delivery systems. Although most of the program's achievements occurred during the last decade of its existence, it nonetheless made some scientific advances during and after WWII—eerily, some designed to take life and others to sustain it. Early on in the program, Fort Detrick developed large-scale fermentation methods to ensure the production of anthrax, botulism toxin, and other agents. Using this expertise, Fort Detrick scientists also contributed to the development of a method to ensure the large-scale production of penicillin during and after the war. One of the challenges of large-scale production of penicillin was the sterilization of the air pumped into the fermentation tanks to prevent contamination. During the war, Fort Detrick scientists developed a filtration system, which in the words of Ira Baldwin—Fort Detrick's first scientific director—"us[ed] a variety of agents to trap and hold various small particles, such as bacteria. This general type of filtration was adopted by the commercial manufacturers of penicillin."[20] Until 1944, penicillin was cultured as a mold in five-gallon glass bottles, from which only small quantities of the slurry could be recovered, making the process cumbersome and costly.[21] Several of the vaccines developed for biodefense purposes were also

shared with civilian health authorities to immunize populations at risk. Examples include scientific personnel working in university laboratories, and hunters and workers in the textile and meat industries who manipulated natural products often contaminated with anthrax or tularemia.[22] Over its lifetime, the program developed about thirty vaccines, half a dozen toxoids, and the same number of new skin tests.[23] Detrick scientists also developed new techniques for purifying, stabilizing, and concentrating pathogens in the laboratory and upon aerosol dissemination. By 1959, the program validated a drying process that allowed tularemia to be aerosolized while achieving the appropriate particle size (5 microns or less) and eliminating electrostatic charge. Until then, most agents were developed in a liquid form, which created storage, transportation, and other logistical challenges.[24]

Several other accomplishments of the bioweapons program contributed to the larger scientific community and are still in use today. These include gaseous sterilization with ethylene oxide, a method used later on in hospitals to sterilize surgical instruments, in the food industry to sterilize spices, and in libraries to kill silverfish. Other key developments included the introduction of high containment (Class III) biosafety cabinets and laminar flow fume hoods. Detrick scientists developed aerobiology techniques and improved methods to investigate the dissemination of bioweapons agents to model the spread of common human viral respiratory diseases. Negative pressure systems were developed to prevent leakage of dangerous agents in the environment, and a new formaldehyde method became a useful means for building decontamination. A version of this decontamination method is still regarded as one of the most effective ways to decontaminate highly pathogenic agents from laboratory settings.[25] Fort Detrick personnel also contributed to the development of the National Institutes of Health biosafety guidelines, and to the design of a sterile laboratory for the Lunar project.[26]

Notwithstanding all of these scientific advances, Detrick scientists' accomplishments were limited in terms of weaponization. Among the two dozen agents studied, only seven human noncontagious agents were produced and weaponized, while five anticrop agents were standardized and produced but not weaponized. Although a variety of delivery and dissemination mechanisms were studied—including bombs, spray tanks, and other experimental processes, such as balloons carrying anti-plant agents,[27] mosquitoes to spread yellow fever and malaria, drones, and marine mines—only a handful were standardized and produced. The first biological weapon was not achieved until 1951, when an anticrop bomb was tested and produced for the Air Force. The first antipersonnel bomb—the M114, weighing four pounds—was produced in 1954 and filled with the incapacitating agent *Brucella suis*. These small bombs were also used to fill the M33 five-hundred-pound cluster bomb, which contained 108 M114s that would disperse and

break up on impact. The M33 and the M114 were tested and filled with a variety of agents, but the military services found none of them satisfactory.[28] For example, the M33 posed logistical problems: due to its short shelf life, it had to be air-delivered from the plant to the appropriate air base; also, it could not be used near the front line due to the risks of infecting U.S. troops.[29] Finally, eight aircraft sprayers were developed, but no missiles were designed to deliver biological agents. Only one warhead filled with bomblets was developed and standardized for the MGM-29 Sergeant missile, but it was not produced in quantity.[30] The list of technical reports from Dugway Proving Ground released in June 2013 indicates that a warhead for the Honest John rocket—the E25 originally developed for chemical weapons—was also tested for the dissemination of smallpox. However, since the report has not been declassified, the outcome of the tests is not clear.[31]

Knowledge, Organization, and Management

However minimal were the successful number of bioweapons, the U.S. program's scientific achievements can be attributed to its ability to exploit its existing knowledge base to the maximum by adopting an organizational and managerial model that promoted personnel proximity, cooperation, and collective work, and that included multiple integrative mechanisms. These features are particularly important to underscore considering the fact that the American program started with a handicap compared to its Soviet counterpart: it had very little bioweapons expertise to rely on and essentially started from scratch.

VAST KNOWLEDGE BASE

When the U.S. program was created in 1943, it received support from the British and Canadian programs, which had begun several years before. Still, the U.S. program essentially started from scratch because little of the British and Canadian work could be adapted to the U.S. program. Whereas the British and Canadian programs were of the artisanal kind, the U.S. program envisioned an industrial-scale project. Therefore, the methods used by America's allies could not be readily adapted or scaled up to achieve U.S. objectives. For example, the British production process, using a series of connected milk churns, was capable of producing only small amounts of agents, making it unsuitable for the large-scale production envisioned by the United States. Consequently, the U.S. program had to create a whole new development and production infrastructure, as well as relevant production processes, requiring several years of exploratory research and testing.[32] What's more, although the British shared their scientific documents and organized scientific exchanges with the United States, access to British results

did not obviate the need to conduct experimental work in U.S. laboratories. Indeed, the novelty of the field for American scientists, and the scale of the work envisioned—radically different from the artisanal size of the British program—necessitated the development of new methods and new knowledge.[33]

To support the adaptation of British and Canadian work to the American context, the U.S. program had access to a large pool of expertise, first from the university system but also from industry. Although the U.S. bioweapons program did not include a cadre of international luminaries as did the U.S. nuclear program, it nonetheless employed scientists who once taught at or received scientific or engineering degrees from elite universities, such as Cornell, Johns Hopkins, Princeton, MIT, Notre Dame, George Washington, American, Georgetown, Northwestern, UC Berkeley, Ohio State, Pennsylvania State, and the Universities of Maryland, Texas, Chicago, Wisconsin, and Pennsylvania, among others. At the tail end of the program, 25 percent of Fort Detrick's personnel—about 500—were degree-holding scientists and engineers, with about 150 PhDs and 100 MS degrees.[34] Many of these individuals were active members of professional associations, such as the American Society for Microbiology (ASM), the American Association for the Advancement of Science, and the American Chemical Society (ACS).[35] It is worth noting that ten of the ASM's presidents worked at Fort Detrick—including scientific directors Ira Baldwin (ASM president in 1944) and Riley Housewright (ASM president in 1966)—and about ten other ASM presidents served as consultants or contractors on the bioweapons program.[36]

In addition, although U.S. scientists had no prior bioweapons expertise, several individuals, who possessed skills directly applicable to bioweapons work, were instrumental in jump-starting the program. For example, Ira Baldwin—Fort Detrick's first scientific director—was a fermentation expert from the University of Wisconsin, possessing expertise essential for scaling up fragile microorganisms. Others, such as Charles Phillips, a chemist from Penn State, and Arnold Wedum, from the University of Colorado, provided essential knowledge for decontamination and laboratory safety, respectively.[37] Throughout its lifetime, the program also made extensive use of outside contractors. A published history of the U.S. bioweapons program lists an impressive roster of contractors commissioned by Fort Detrick, including 186 private firms and laboratories operating in agriculture, biology, chemistry, and aviation, as well as 78 top medical schools and universities, such as Columbia, Cornell, Yale, Duke, Harvard, Northwestern, Princeton, Stanford, George Washington, and Pittsburgh (see Appendix 1).[38] Fort Detrick also received support from outside consultants and advisory committees created within prestigious professional organizations, such as the ASM, the ACS, and the National Academy of Sciences.[39] Finally, the U.S. Army, Navy and Air Force provided scientific and weaponization expertise. The U.S. program was therefore able to assemble a knowledge base capable of ad-

dressing the challenges of bioweapons development, production, and weaponization.

ORGANIZATION: PROXIMITY, MOBILITY, SOCIAL CONTEXT, AND SYSTEM INTEGRATION

At the organizational level, the program adopted a model ideally suited to exploit this knowledge base. Unlike its Soviet counterpart, which had a scattered and fragmented structure, the U.S. bioweapons program was organized around a central facility—Fort Detrick—which investigated all of the stages of a bioweapons life cycle, while the two other facilities—Pine Bluff production plant and Dugway Proving Ground—were specialized satellites performing large-scale production and open-air testing. Structurally, Fort Detrick's organization was reminiscent of that of the "industrial district," discussed in chapter 3, where personnel proximity, mobility, and social interactions were essential mechanisms for knowledge creation and transfer. The complex also included integration mechanisms to ensure the coordination and synchronization of stages within and between facilities.

Proximity within the U.S. bioweapons program was part of a stated policy to foster knowledge diffusion and the integration of the program's subparts. A booklet describing Fort Detrick's activities indicates that "to the greatest practical extent, physical co-location of program responsibilities within a single center makes it possible for management and technical personnel to work in close personal contact, thus improving control and reducing lead time for a given commodity."[40] Fort Detrick was indeed a microcosm of the U.S. bioweapons program: it concentrated in one location all of the stages of a bioweapons life cycle, starting from research and development, moving to production, and ending with testing and weaponization.

To conduct all of these activities, Fort Detrick gathered under the same roof all of the skills and disciplines required to support defensive and offensive work on a variety of agents causing human, animal, and plant diseases. These included medical doctors, virologists and bacteriologists, biochemists, veterinarians, zoologists, plant disease specialists, biological engineers, chemical engineers, mechanical engineers, mathematicians, statisticians, physicists, aerobiology specialists, and explosive specialists. To support the operation of the facility, Fort Detrick had an in-house animal farm, as well as an Engineering Division with a machine shop that maintained, repaired, and even designed and produced the facility's equipment when it was not available commercially. On-site support staff—laboratory technicians, animal caretakers, welders, plumbers, electricians, and machinists—enabled the operation of the laboratories and production facilities on an around-the-clock basis.[41] The Procurement Division and its warehouse purchased everything needed for its laboratories, from lab coats to biological material, primates, laboratory animals and their food, lab equipment, raw material for

the machine shop, and other necessary supplies for the various bioweapons research and support departments. Fort Detrick was therefore structured to operate as a technical incubator, where scientific and production processes were developed, tested, and confirmed before being adopted and transferred to the next stages: large-scale production at Pine Bluff and open-air testing at Dugway Proving Ground.

As with industrial districts, personnel at Fort Detrick were mobile within the facility and between the three facilities of the program. Personnel mobility was part of a formal policy to employ all of the skills available within the organization, regardless of the organizational lines of authority. For example, a booklet describing the operation of the Development and Engineering Laboratories at Fort Detrick indicated that "specific missions frequently necessitate the formation of teams of best qualified persons drawn from anywhere in the organization. Lateral movement of persons, as necessary, between divisions is accomplished to fulfill the mission undertaken."[42] Thus, Fort Detrick had a stated policy of creating new knowledge teams in response to specific scientific and technological challenges through personnel mobility. As a result, although the laboratories and production facilities were organized into specialized directorates and divisions, and personnel were spread out accordingly, a high level of cooperation existed between and among the divisions and their personnel. Personnel from one division were routinely involved with the work of other divisions, thus cross-pollinating their respective knowledge. Even the divisions that in theory worked independently, such as the crops division, or that were highly compartmentalized, such as the CIA's Special Operations Division, routinely involved personnel from other divisions at Fort Detrick to conduct various projects.[43]

To facilitate mobility and information exchange, personnel working within the security fence at Fort Detrick had the same security clearances. Although information was in theory released on a "need to know" basis, management's emphasis on information sharing encouraged personnel to communicate more freely among colleagues who were authorized to handle the data.[44]

Unfettered communications were further permitted by the high level of socialization that pervaded the organization. Several factors contributed to personnel socialization: First, most of the Detrick staff after the Second World War were returning veterans of roughly the same age, creating a common cohort. Second, scientific personnel who were typically hired from other parts of the country lived within the Fort Detrick base because sufficient housing was not available in the city of Frederick, Maryland, in the early years of the program. Third, as a military installation, Fort Detrick offered several amenities and social opportunities that were not available in the small town of Frederick, including a swimming pool, a bowling alley, and the opportunity to buy liquor in a county that was then dry.[45] These conditions allowed the creation of long-lasting friendships that sometimes

crossed organizational—as well as hierarchical, educational, and racial—lines.[46] For example, one of the pilot plant shift supervisors, now a renowned fly fisherman, indicated that he would often go fly fishing with a group of friends that included pilot plant technicians as well as engineers and scientists from the various divisions, some of whom had managerial positions.[47] Although the passage of time surely has a way of fostering the "good old days" of Fort Detrick rather than any darker incidents that may have prevailed at times, individuals at Fort Detrick appeared to be more consistently willing to share information and experiences to help one another compared to those in the Soviet program. This amiable work environment seems to have both fostered problem solving and promoted the creation of new knowledge, born of a collective and cooperative interpretation of information.

Several integrative mechanisms embedded within the workflow at the facility level and between the facilities comprising the overall bioweapons complex supported personnel proximity, mobility, and socialization. These included functional overlap, system integrators, and liaison officers who served as communication nodes and helped coordinate and synchronize work among the disparate parts of the program. Unlike in the Soviet program, where the stages of a bioweapons life cycle were disconnected and organized according to an assembly-line model, in the U.S. program, the workflow is best depicted as a feedback loop, where at each stage of its development the product was tested for certain properties and returned to the previous stage if those properties were not met. To allow the transfer of knowledge and the successful passage from one stage to the next, the program used the concept of functional overlap and transition teams: scientists and technicians followed a product to the next stage to assist their colleagues in solving problems. For example, after the completion of a product development process, a team of five to six scientists from the Product Development Division would go to the pilot plant to help adapt the production process to the pilot plant's conditions.[48] A former bioweapons scientist described the transition process as follows:

> There was a big exchange of information, and when the candidate [agent] moved out of the research area into the small scale work and into the bigger pilot plants, there was always this transition . . . where people from the research area would actually come with us and work in the lab to find out why something was not working.[49]

A similar transition system existed between Fort Detrick and the testing site at Dugway Proving Ground and the production plant at the Pine Bluff Arsenal.[50] For example, whenever Fort Detrick developed a new production process for a particular agent, a team of scientists from the Product Development Division would travel to Pine Bluff, sometimes for extended periods of

time, to help with the adaptation of the production process to reach industrial-scale quantities. As a former Fort Detrick product development scientist noted:

> We developed the processes for the manufacture of VEE [Venezuelan equine encephalitis], and I went down . . . six weeks to Pine Bluff to help implement the processes. The reports were obviously good, but again they don't give the amount of detail that a person to person [interaction allows].[51]

Safety Division and Product Evaluation Division staff would also periodically visit Pine Bluff and Dugway to help with transition and troubleshooting.[52] Notably, the scientists and engineers working with the 8-ball aerosol test sphere collaborated closely with testing staff at Dugway Proving Ground to compare their respective test results.[53]

To reinforce the coordination of its component parts, the U.S. bioweapons program had among its staff several individuals who served as system integrators. Their role was to ensure the exchange of information between Fort Detrick, the Pine Bluff production plant, and the Dugway testing site. For example, Fort Detrick had among its staff four individuals who were formally responsible for serving as liaisons between the Fort Detrick and Pine Bluff facilities to ensure the successful transition to large-scale production.[54] These individuals were usually heads of production divisions, with specialized experience in different categories of agents. To fulfill their role efficiently, these system integrators had to possess certain qualities. Most important of all, they needed to have a scientific or technical background composed of not only academic knowledge but also knowledge and skills acquired through extensive practice. Additionally, because the work conducted at Fort Detrick entailed a variety of disciplines, these system integrators also had to possess experience in, or knowledge of, several other disciplines, in order to understand each unit's respective jargon and concepts so as to translate them into those of another discipline. As noted in chapter 3, one of the liaison officers between Fort Detrick and Pine Bluff had a degree in microbiology and biochemistry, and through his successive positions as manager of the virus pilot plant, chief of the Agent Process Branch, and head of the Product Development Division, he conducted research and production activities related not only to viruses but also to bacteria and rickettsiae.[55] Another had a degree in chemical engineering and some training in electronics. He also held various positions managing the production of bacterial agents, and later headed the Crops Division. In these positions, he became intimately familiar with research, production processes, and delivery systems of various agents causing plant, human, and zoonotic diseases.[56] As the former head of the crops division put it:

> [The liaison officer] was responsible to see that everybody cooperated and coordinated; [this] coordinating position required more people skills and making sure that the team doing this phase or that phase did not get out of sync or [become] dissatisfied with the other one, and become competitive in some way or another.[57]

Other individuals and divisions served as informal system integrators by virtue of their positions or their respective roles within the organizational workflow. Because they were at the intersection of several stages and tasks, these individuals and divisions became communication nodes that redistributed information gathered throughout Fort Detrick and beyond. For example, the Product Evaluation Division (PED), including the 8-ball aerosol test sphere, was a central interaction node within Fort Detrick, because it evaluated and tested the work of all the divisions involved in research, production, and weaponization of pathogens.[58] Not only did PED have broad knowledge of these divisions' activities, but because of its central role in the workflow, it was able to identify and help solve a variety of the problems that each of these divisions encountered during testing. This facilitated the use and integration of ideas and concepts throughout the whole organization. The Safety Division was another major system integrator within the facility. Safety personnel worked with all of the divisions within Fort Detrick and were able to identify and propose solutions to safety problems that could be shared across the whole facility.[59] Because of their involvement with upstream and downstream stages, these two divisions ensured the functional overlap of Fort Detrick's component parts, allowing decision making at one stage to take into account the constraints of another stage.

These organizational and integrative mechanisms favored the cross-pollination of knowledge, the creation of a transactive memory, and the diffusion of explicit and, more importantly, tacit knowledge throughout the bioweapons complex. These conditions were essential for allowing the collective resolution of interdisciplinary problems and promoting innovation.

MANAGEMENT STYLE: LOOSE HIERARCHICAL RULES, TRUST, AND COGNITIVE COHESION

These formal integrative mechanisms would not have resulted in the efficient transfer of knowledge without the intervention of Fort Detrick's scientific directors. Originating from the university system, Fort Detrick's two longest-serving scientific directors were acutely aware of the importance of ensuring openness, cooperation, and learning to make progress. In addition, scientific managers designed an integrity system that fostered trust and encouraged personnel contributions to the improvement of scientific processes.

First scientific director Ira Baldwin can be credited for creating the corporate culture that fostered the conditions required for innovation. From the outset of the program, Baldwin aimed to flatten the vertical structure of the military organization by establishing the dominance of civilian culture over military culture. The goal was straightforward: to resist military intrusions in scientific decisions. He opted to remain a civilian during WWII—and even remained on the University of Wisconsin's payroll—because, as he put it, "as long as I wore a red necktie I could say no to anybody."[60] Conflicts with the military started early with General Kubrick, who was responsible for overseeing the establishment of the bioweapons program in 1942. In the words of Ira Baldwin, "General Kubrick held conferences on everything under the sun. . . . He had quite a temper. . . . And at times these conferences became quite heated. . . . I did not find it a particularly conducive atmosphere to get much work done."[61] Clashes with the military culture also manifested themselves in the form of organizational challenges. Protocol dictated that military rank had precedence over scientific competence. For example, Charles Rush Phillips, who developed several of the new sterilization and decontamination techniques at Fort Detrick, was a chemistry professor at Penn State University before joining the program in 1943. In spite of his scientific credentials, he was placed under the authority of a sergeant in the Decontamination Division because he came to Fort Detrick as a private.[62] Baldwin indicated that military protocol required the use of inventive organizational schemes, often resulting in placing competent scientists, who nonetheless had a low military rank, at the head of teams primarily made up of civilians to avoid conflicts with the military hierarchy.[63] Other conflicts erupted with the military hierarchy due to Baldwin's emphasis on safety regulations, which military officers viewed as an impediment to faster progress in facility construction and scientific work. For example, when General Rollo Ditto—assistant chief of the Chemical Warfare Service (1943–1946)—attempted to replace a biological engineer selected by Baldwin with a candidate with no biological experience because he thought the work was going too slowly, Baldwin threatened to resign. The general eventually retreated, although he placed his candidate under Baldwin's engineer.[64] British scientists such as Lord Stamp and David Henderson, who were based at Fort Detrick during the war, also joined that chorus and deployed some of their connections in the military and political establishment to challenge Baldwin's authority.[65] Although Baldwin lost some of these battles, he often prevailed by putting his job on the line.[66] His expertise in the field of large-scale fermentation was essential for the production of industrial quantities of bio-agents, which gave him some power in his dealings with the military hierarchy.

Affirming the dominance of the civilian culture within Fort Detrick was also made possible by the regular increase in civilian scientists compared to military personnel. At the outset of the program, the urgency of the war allowed Ira Baldwin to recruit among colleagues at the University of

Wisconsin and other academic institutions, who in turn recruited among their friends. This recruiting system allowed the organization to create a nucleus of academics who knew one another and could re-create within the program an open environment of academic collaboration, in spite of the high level of secrecy imposed by the war. Baldwin himself indicated that this helped dampen the influence of the military, particularly that of General Kubrick. As Baldwin put it, "Ultimately though, we got more of us [civilians] and then began to get a little order at Edgewood where we could start working."[67] Further decreasing the influence of the military culture, many of the enlisted personnel left the program after the war to be replaced by civilians in the late 1940s. By the end of the program, 1,800 of the 2,000 or so employed at Fort Detrick were civilians.[68]

All of the scientists and technicians interviewed for this book indicated that the culture created by Baldwin was preserved during the postwar period under Dr. Riley Housewright, Fort Detrick's longest serving scientific director (1956–1972). Having served under Ira Baldwin and being a civilian himself, Housewright instilled within the hierarchy a spirit of openness and flexibility, which substantially reduced unnecessary hierarchical and administrative hurdles. In addition, starting in 1947, civilian managers primarily handled the scientific and production work at Detrick.[69] Comparable to the Manhattan Project, Fort Detrick's military and civilian management established a clear distribution of responsibilities between them. The role of Fort Detrick's military commander was limited to the administration of the facility's territory and services, while the scientific director managed all technical work and laboratories involved in the development of bioweapons.[70] Although Ira Baldwin left the program in 1945 to return to his position at the University of Wisconsin, he remained involved in decision making for the program by chairing the Committee on Biological Warfare (CBW)—an advisory committee to the Pentagon. In 1947, the CBW recommended that classification rules be relaxed to allow more open work, which the Pentagon accepted.[71] Although some conflicts between civilian and military managers continued to arise occasionally, former Fort Detrick scientists and technicians indicated that these disputes did not trickle down to scientific levels.[72]

Fort Detrick's management also encouraged all personnel—from technicians to senior scientists—to become involved in improving not only technological output but also organizational processes and procedures that would allow the facility to make progress or ameliorate security and safety issues in bioweapons work. To foster broad participation, Fort Detrick took the standard practice of a suggestion box seriously as an incubator for new ideas and practices. To ensure full integrity in the process, a "suggestion committee"—made up of personnel representing various divisions and levels of the hierarchy—reviewed employee ideas periodically.[73] As Fort Detrick was a relatively small organization where people communicated freely, due in part to commonly shared security clearances and the high level of

social interaction, the committee members were aware of new developments in the various divisions and branches and could determine whether someone who had proposed a new idea was trying to get credit for another scientist's work. Although this occurred occasionally, the committee's review created a safeguard that protected personnel contributions. According to former Fort Detrick personnel, these conditions were instrumental in generating a trusting and cooperative work environment.[74] A side effect of the suggestion committee was the informal review process that it generated. Because news traveled fast within such a flat organization, people learned to make sure that their results were repeatable before submitting them for review or testing.[75] Individual achievements were also recognized through a variety of compensation schemes, ranging from pay raises and promotions to patents for new processes and other types of public recognition.[76]

This approach not only ensured the transmission of ideas throughout the organization but also encouraged all personnel to become more engaged and productive. For example, although the U.S. bioweapons program gave marginal importance to publications, Fort Detrick personnel and contractors published 1,616 journal articles in the open literature about their scientific and engineering work between 1946 and 1972, which is substantial given the classified context of the work.[77] Although publications during the war were restricted, several of the articles published in the postwar period were based on wartime research. Tellingly, between October 1945 and June 1947, 156 papers based on wartime research were cleared for publication, and by the latter date, 121 had been published.[78] The ASM alone catalogs over 500 articles published in its scientific journals by Fort Detrick personnel between 1946 and 1969; several of these are high-ranking journals, such as *Molecular and Microbiology Review*, the *Journal of Bacteriology*, and the *Journal of Virology*.[79] It is worth noting that the ability to continue publishing was used as a recruiting tool after the war, to attract scientists from academic institutions.[80]

Unlike academic scientific organizations, scientists at Fort Detrick did not have to publish their scientific findings to be promoted or recognized. Although competition can foster innovation and embolden staff to outdo others in some circumstances, at Fort Detrick it was the lack of academic competition that had the effect of promoting innovation, by encouraging a cooperative environment in which personnel could freely share their ideas and work together. This was further reinforced by the Detrick integrity system, wherein technical staff had safeguards to protect against others exploiting their achievements.[81] As the chief of the Product Evaluation Division observed:

> We published a lot of scientific papers; not my group so much because I tended to be on the applied end, and much of it was classified, and little of it would have any impact in the scientific community. But the basic research

> people, they published a lot. But again it was not "publish or perish," you see; we worked together.[82]

The absence of academic competition also had a positive impact on training and skills development within the organization.[83] As personnel were encouraged to share information and cooperate with one another, they more readily shared data and skills compared to organizations with a less cooperative environment.[84] Within Fort Detrick, failures were viewed as part of the learning process and were used to improve existing knowledge, not to stigmatize the failing team.[85] Improved communication and learning between different disciplines were also fostered by formal training schemes. For example, as a means of expanding interdisciplinary knowledge, science courses were organized within Fort Detrick for engineering and support personnel. Engineers had to take semester-long courses organized by a Fort Detrick scientist on bacteriology, laboratory-animal uses, and injection of animals.[86] Several members of the technical staff also pursued PhD studies while working at Fort Detrick, taking night classes at the University of Maryland or Johns Hopkins University.[87] The institutionalization of knowledge also occurred via the organization of monthly meetings among divisions cooperating on a specific project, as well as through quarterly in-house conferences, during which each directorate presented a work update to the wider group.[88]

Openness within the U.S. bioweapons program also manifested itself through collaborations with scientists outside the bioweapons complex. In spite of the secrecy of its work, Fort Detrick routinely provided data or strains to public health or university researchers to support scientific inquiry in various areas. For example, over sixty articles were published in ASM journals between 1948 and 1969 by non-Detrick researchers based on material or data provided by Fort Detrick.[89] Fort Detrick also welcomed and integrated knowledge created in unclassified spaces by other organizations into its knowledge base. The integration of outside knowledge materialized in several ways. For one, existing personnel were allowed, and sometimes required, to obtain additional training to expand their skills. Fort Detrick also routinely integrated new blood into its facility through the "semi-professional and professional program" (SP&P), which allowed young men who had been previously trained in laboratory science to fulfill their two-year required military service through work at Fort Detrick. This openness to the outside world was not insignificant: it created external communication channels, allowing the organization to benefit from new developments or innovations generated by industry and the academic world, thus extending the pool of knowledge available to the organization.

Finally, although the bioweapons program encountered problems hiring and retaining personnel after the Second World War, a large portion of those who joined during the postwar period remained until the end of the program

in 1969. This promoted continuity in personnel interactions, allowing practitioners to sharpen their skills as well as accumulate and share knowledge over a long and continuous period of time. Reinforcing this trend was the fact that, unless required for the study of new problems, the composition of teams of technicians and scientists was seldom modified, thereby permitting the same individuals to work together for lengthy periods of time.[90] This further enhanced the creation of standards of practice and the institutionalization of knowledge.

The combination of organizational and managerial characteristics of the U.S. program resulted in a knowledge management model particularly well suited to deal with novel and complex scientific problems. The proximity and mobility of personnel supported by a favorable social environment permitted easier transfer of tacit skills and easier adoption of new technologies to solve such challenges. The collaborative and open culture allowed personnel to create a library of expertise available within and outside the program—transactive memory—to access a larger pool of expertise to solve problems collectively. Finally, the learning and open work environment along with the integrative mechanisms allowed the creation of cognitive cohesion among the staff to tackle interdisciplinary problems and facilitate the passage from one stage of a bioweapons life cycle to the next. With such favorable circumstances, it is puzzling that the U.S. program failed on the weaponization front, notwithstanding its scientific achievements. This is a case in which seemingly favorable endogenous variables can give an incorrect picture of a program when they are analyzed independently from exogenous variables. In the U.S. case, exogenous variables dampened the positive effect of the organizational and managerial model and weighted heavily on the program's pace and outcome.

Weight of Exogenous Factors on Program Results

The American bioweapons program illustrates a theme that, as we will see in the next chapters, constitutes a key impediment to successful weapons development: the lack of coordination and focus within and between agencies involved in programmatic decisions and funding. In the U.S. program, at least a dozen agencies, with different and at times conflicting requirements and schedules, made often uncoordinated decisions affecting the program. With no central coordinating agency at the highest governmental level, and no heterogeneous engineer who could advocate for the program in a sustained manner throughout the program's lifetime, political and military establishments gave low priority to biological weapons, leading to fluctuating funding and interest for the larger part of the program's twenty-seven-year life span.[91] Given the admittedly stiff challenges of producing and weaponizing live organisms subject to unpredictable and unreliable

performance, it is no surprise that the program experienced such uneven support and consistently weak direction from senior governmental authorities, leading to a dissipation of funds. This lack of coordination and focus not only gave the American bioweapons program the appearance of a patchwork of disparate projects, serving different goals and purposes, but also operated as an on/off switch, which generated numerous perturbations in work continuity and stability at the facility level, and further complicated the design of a reliable weapon that met military requirements.

LOW POLITICAL AND MILITARY PRIORITY

Biological weapons were never considered a political or military priority for the United States, especially with the advent of the atomic bomb and its demonstrated destructive power. From the outset, President Roosevelt devoted little attention to the program, limiting his interventions to acceding to funding requests, at times without reading their justification. Although divergent views were discussed at the highest level about bioweapons use—some recommending retaliation only, others exploring first use, still others emphasizing the immoral character of biological weapons—Roosevelt himself did not seem to give much thought to such issues. Historian Barton Bernstein notes that in all of Roosevelt's papers, only about a dozen dealt with biological weapons, and most concerned procurement or administrative matters.[92]

Although Secretary of War Henry L. Stimson pushed for the initiation of the program, his support was accompanied by apparent moral misgivings. He insisted that the program be managed by a civilian organization—the War Research Service (WRS), headed by George W. Merck, because "biological warfare is a dirty business."[93] Reports produced by the WRS, however, were scant, and there is no evidence that Stimson was interested in the details of the program or that these reports were also sent to the president.[94] This initial disinterest in bioweapons among political and military elites was perpetuated up until the early 1960s, when Secretary of Defense Robert McNamara attempted to provide more direction to the program. To that end, he sponsored a plan—known as Project 112—that laid out precise tasks and target dates to achieve a bioweapons capability that could be used during a limited war. Project 112 also required either the secretary of defense's direct approval or, in some cases, presidential approval for some testing and research activities.[95]

Generally, however, political and military interest in bioweapons increased sharply in times of crisis and fell off substantially as crises subsided. During the Second World War, the bioweapons program, which had started in 1941 and was still at the embryonic stage under the Chemical Warfare Service, dramatically expanded following the Japanese surprise attack on Pearl Harbor. It was also supported after faulty intelligence indicated that the

Nazi regime might use botulinum toxin in Europe. By the end of WWII, the program had received $60 million to establish a research, production, and testing infrastructure, as well as to engage a large number of universities and private companies in bioweapons-related work.[96] But enthusiasm for bioweapons fell dramatically after the successful development of nuclear weapons, which contrasted sharply with the comparable lack of swift progress in the bioweapons program. As a result, at the end of WWII the program was almost terminated. Major construction and testing activities ended. The Horn Island test site was closed. The Vigo plant, whose construction was just completed in May 1944, never produced infectious agents.[97] Research activities were consolidated at Fort Detrick, and the research agenda was sharply decreased. The number of personnel reached an all-time low, dropping from about 4,500 during the war to less than 500 afterwards.[98] During the postwar period, the program was maintained on life support due to the emergence of the Cold War. The budget remained low, $2.7 million in 1947, increasing to an average of $5 million per year until 1950.[99] (See Appendix 2 for budget figures.)

With the Berlin Blockade in 1948, followed by the Korean War (1950–1953)—both of which threatened general war—military and political interest in bioweapons reawakened once again. A crash program was launched in 1951, and the program's budget rose to a total of about $350 million for the 1951–1954 period alone. Of this total amount, an average of $19 million per year was devoted to bioweapons research and development, and about $150 million supported the largest expansion of the program's infrastructure in its history.[100] This included the construction of several new laboratories at Fort Detrick; a large-scale production plant in Pine Bluff, Arkansas, which alone cost about $90 million; and the establishment of the one-million-liter test sphere for pathogens and munitions at Fort Detrick.[101] The research agenda spread to new areas, including research on antipersonnel, anti-animal and anti-plant agents. The Korean War was also the period during which military authorities became most invested in achieving a bioweapons capability for use on the battlefield. Already in 1949, the Air Force had developed plans to use bioweapons had the Berlin Blockade turned into a general war. These plans were maintained during the Korean War, and in 1952, General Twining—Air Force vice chief of staff—issued a directive requiring the Air Force to reach an operational bioweapons capability within two years to load the whole fleet of medium bombers with standardized anticrop, anti-animal, and antipersonnel agents by July 1, 1954.[102] Progress was slow to materialize, however, and by 1953, as the Korean War was winding down, the military's interest in bioweapons once again turned desultory. Six weeks after the end of the Korean War, the crash program was terminated.[103]

Enthusiasm for bioweapons reemerged at the tail end of the Eisenhower administration, and continued in the aftermath of the botched Bay of Pigs

invasion and the Cuban Missile Crisis. Faced with a potential conflict with the Soviet Union, Secretary of Defense McElroy ordered a review of the biological weapons programs, which concluded that the program had made slow progress due to funding restrictions. Another review, launched under the Kennedy administration in 1961, concluded that reaching the chemical and biological weapons goals as defined by Secretary of Defense Robert McNamara would cost about $4 billion.[104] Although the bioweapons budget did not reach the stated amount, it nonetheless increased significantly. A first expansion occurred under McElroy, with a suggested fivefold increase in the budget over five years, and the creation of the Biological and Chemical Defense Planning Board (BCDPB), responsible for establishing clear objectives. The armed services were directed to increase their respective bioweapons budgets to meet the objectives articulated by the BCDPB, which were to achieve a retaliatory and defensive capability. Already in 1959, the armed services had started submitting requirements for bioweapons to the Army Chemical Corps, including artillery shells, missiles, drones, and other weapons. Under McNamara, Project 112 resurrected the development of anticrop agents (formerly abandoned after the Korean War), emphasized work on incapacitating antihuman agents, and improved testing capabilities, which led to the activation of the Deseret test site in Salt Lake City, Utah, in 1962.[105] The Vietnam War (1963–1972) sustained interest in bioweapons, although greater emphasis was placed on anticrop agents—particularly chemical defoliants—and incapacitating agents.[106] This renewed interest permitted an increase in the program's budget, reaching the total amount of $42 million in 1963.[107] Three years later, however, the Vietnam War's increasing budgetary constraints, growing opposition to the conflict, and international efforts to ban the use of bioweapons eclipsed the short-lived revival of interest in bioweapons. After another three years of diminishing budgets, President Nixon formally terminated all offensive bioweapons work.[108]

DIFFUSE ORGANIZATION AND LACK OF COORDINATION

The on-again-off-again interest in bioweapons was aptly reflected in the program's organizational makeup. Unlike the U.S. nuclear weapons program, which was placed under the unified management of the Army Corps of Engineers during WWII, and later under that of three successive agencies,[109] the U.S. bioweapons program never benefited from a unified management. About a dozen agencies shared responsibilities and made funding decisions for the program throughout its lifetime. These included the Office of the Surgeon General, which had responsibility for biodefense; the Navy, which funded and conducted research at its own laboratories and at Fort Detrick; and the Central Intelligence Agency, which independently ran the Special Operations Division at Fort Detrick, responsible for the development of assassination agents and other black operations gadgets. Moreover,

the Army Chemical Corps and the Air Force shared responsibility for defining and funding other research goals for the bioweapons program. Other agencies, including the Public Health Service, the Department of Agriculture, the Department of the Interior, and the National Academy of Sciences, also engaged in shaping decisions.[110]

Multiple reorganizations also plagued the U.S. bioweapons program. In 1942, the WRS, headed by Merck, held oversight authority over the program.[111] Two years later, however, the WRS was abolished and replaced by the U.S. Biological Warfare Committee, with Merck serving as a consultant.[112] In 1947, management of the program was transferred again to the newly created Office of the Secretary of Defense (OSD). Within OSD, the Research and Development Board—composed of Department of Defense staff and consultants, representing science, industry, and government—held general oversight responsibility over the program, while the chief chemical officer oversaw work conducted at Fort Detrick. In October 1953, a new reorganization resulted in the creation of an assistant chief chemical officer for bioweapons within OSD, under which all bioweapons components of the Army Chemical Corps were consolidated. This new reorganization was meant to both facilitate the outsourcing of bioweapons work to a commercial company and improve preparedness in view of a potential bioweapons use during the Korean War. Negotiations with the private chemical company, however, failed, and a year later, in 1954, the position of assistant chief chemical officer was abolished.[113] Another round of reorganization commenced in 1962, when the biological weapons program was placed under a newly formed Munitions Command subordinate to the Army Materiel Command. Although Fort Detrick remained the central facility of the biological weapons program, with operational control over production activities at Pine Bluff, testing and evaluation of biological agents was assigned to a separate Testing and Evaluation Command.[114]

In the midst of the fluctuating interest and organizational changes, the program did not benefit from the sustained actions of a heterogeneous engineer. Although several individuals supported the program—including George W. Merck, who presided over the program's creation, as well as several senior military officers—none acted to coordinate the programmatic and funding decisions of the various agencies involved in overseeing the program throughout its lifetime. Many also had misgivings about either the morality or military value of bioweapons, which further prevented sustained focus on the program over time.[115] Multiple administrative reorganizations of the program also contributed to prevent the emergence of a sustained and powerful coordination function. The posture of Colonel William S. Bacon—Fort Detrick's first commanding officer—provides a telling illustration of the dilemma that many faced. Ira Baldwin indicated that although Bacon was well connected and zealously used his contacts in Washington to obtain the resources that the nascent bioweapons program needed, he did not want to

be associated with the program. Having served in the chemical service during World War I, Bacon believed that a congressional inquiry would undoubtedly take place to investigate the bioweapons program, and he did not want to have to justify his actions. Therefore, he scrupulously conducted business related to the program orally and rarely left a paper trail of his actions vis-à-vis the bioweapons program.[116] He also served only six months as Fort Detrick commander (April–September 1943), and the tenure of subsequent commanders—a total of eighteen—lasted from just a few months to two years, which proved hardly enough time to ensure the kind of sustained support required for work stability and continuity throughout the program's life span.[117]

The absence of a heterogeneous engineer and a central coordinating agency, together with multiple administrative reorganizations, resulted in a dispersed research agenda, in which objectives were defined by individual agencies, often without coordination. This was particularly the case within the armed services, which controlled not only a portion of the budget but also the research agenda conducted by the laboratories and the personnel they dispatched to Fort Detrick. The lack of coordination was most apparent when the bioweapons program rose in priority during international crises. For example, when in April 1944 George Merck proposed to shift emphasis from bacteriological agents to crop defoliants for potential use against Japan, the armed services adopted different postures. The Army Chemical Corps saw potential in the idea, but it raised concerns about the moral aspect of destroying life by poisoning food sources. Conversely, the Air Force first embraced the idea and started to draw plans to use anti-rice agents, but it quickly reversed course, arguing that destroying cities was more effective. Nevertheless, the assistant secretary of war for air, Robert Lovett, approved plans for destroying Japan's rice crop. Fortunately, the war ended before these plans could be implemented.[118]

Similarly, when the Korean War gave more urgency to the bioweapons program, the Chemical Corps developed the M33 cluster bomb to disperse dry agents. The Air Force ordered 23,900 of these bombs, which soon proved to be inefficient and logistically burdensome: in tests, the Air Force determined that to cover thirty target areas, each consisting of thirty square miles, 17,000 bombs would be needed. Moreover, a staggering 1,221 transport aircraft would have been required to achieve the desired effects.[119] The Air Force subsequently grew disillusioned with Fort Detrick's ability to produce an effective bomb and sharply reduced its financial support for the bioweapons program from $5.7 million in 1953 to $1 million in 1956, while redefining the program's objectives to emphasize research and testing. The Army, on the other hand, continued its support in spite of the program's inability to develop the required weaponry.[120] During the same period, the Army and Air Force also collaborated to develop a spray tank for the Marine Air Wing and the Air Force. The common project, however, progressed slowly,

which led the Air Force to launch an independent spray-tank program that was completed in April 1953. In another example, in 1957, the Army decided to end development of anti-plant agents at Fort Detrick, because those agents primarily supported the Air Force. All anti-plant activities were effectively shut down by 1958, only to be restarted a year later, this time with support from the Air Force, which anticipated that such agents might be needed if hostilities in Vietnam were to spread. Consequently, Fort Detrick had to restart formerly abandoned work, leading to delays in achievements.[121] In 1961, Secretary of Defense McNamara attempted to harmonize decision making within the DOD when he placed the biological weapons program under the authority of the Army Materiel Command. Unsurprisingly, the reorganization failed to centralize decision making for the bioweapons program, because it did not remove funding authority from individual service agencies, allowing them to continue taking the program and its paltry funding in disparate directions. For example, even after the 1961 reorganization, the Navy and Air Force still continued to fund their own bio-related research projects.[122]

The lack of coordination was also a common feature within the services. In 1951, a report by the inspector general criticized the Air Force for its uncoordinated bioweapons program and its lack of a central coordinating agency. In response, General Twining—responsible for operational planning of bacteriological warfare—set up a new organization to coordinate the Air Force program. He also issued the "Twining directive" in 1952, which required that all units of the Strategic Air Command become bioweapons operational within two years. This new objective, however, was defined without much coordination with the scientific staff at Fort Detrick. Twining had effectively made bioweapons operational before they were sufficiently developed and tested, and, not surprisingly, his expectations went unmet.[123]

The Twining episode was symptomatic of a larger problem that hampered progress throughout the program: the insufficient collaboration between scientific researchers and military users. A 1950 report of the Committee on Biological Warfare recommended "that measures be taken to insure maximal collaboration between research personnel and representatives of 'using' services and other government agencies concerned during study of specific requirements of BW items, and that such collaboration . . . be maintained during the applied research development, and technical evaluation phase."[124] The recommendation fell on deaf ears.

Similarly, Secretary of Defense McNamara's 1961 Project 80 committee reviewed the organization of the Army and found that the Chemical Corps was not well integrated with combat troops, which limited the spread of the Chemical Corps' accumulated expertise to benefit the rest of the Army, especially in the field of troop training. Colonel John Palmer, heading the Chemical Corps Training Command, summarized the problem as follows:

"Much of the Army still appears to visualize . . . biological warfare training as an annoying distraction from normal combat training."[125]

DISRUPTIONS IN SCIENTIFIC WORK

Not surprisingly, the unsettled and dysfunctional nature of the U.S. bioweapons program affected scientific work. Post-WWII military demobilization saw most of the scientists who came from the university system return to their former positions. When the program was reenergized in the late 1940s due to the Soviet threat, the talent pool had to be reconstituted. More importantly, much of the tacit knowledge accumulated during the war was lost, requiring the new recruits to re-create a substantial knowledge base. When the departing military staff were replaced by new civilian recruits, the overlap between them was not sufficient to transfer the knowledge accumulated during the war. A former shift supervisor at Fort Detrick's pilot plant, who joined the program in December 1945, indicated that his overlap with departing military personnel in the pilot plant lasted only about two months, forcing him to learn most everything on the job.[126] A laboratory technician, who started work at Fort Detrick in 1950, said he received no formal laboratory training. Six months after his arrival, he became infected with brucellosis while working in the laboratory with pipettes.[127] There seems little doubt that limited exposure to more skilled colleagues, as well as the limited availability of safety equipment, contributed to such accidents.[128] Bill Patrick—former head of the Process Development Division—was recruited at Fort Detrick in 1952 by his former professor from the University of Tennessee, who was doing research on viruses at Fort Detrick. However, by the time Patrick received his security clearance and reported to work, his former professor had left the bioweapons program to return to academe.[129]

Cumbersome army personnel regulations also complicated Fort Detrick's ability to attract and retain expert staff by virtue of imposing salary caps and limits on the overall number of employees.[130] A report by the Committee on Biological Warfare, issued in January 1950, indicated that Army personnel regulations "interfere[d] with the creation and continuity of [scientific] teams," and sought the elevation of the bioweapons program to a level of priority more comparable to the nuclear program's in order to ensure "stability and continuity of effort in BW research and development."[131] Thus, when interest in bioweapons intensified during the Korean War, the bioweapons program was still in the initial phase of re-creating its knowledge base—much less expanding its industrial base—leaving the program incapable of rapidly supporting urgent military needs.

Additionally, for most of its life the bioweapons program operated with insufficient infrastructure to meet military requirements. Up until the 1950s, the bioweapons program was primarily a research and development

endeavor, which operated with temporary facilities. During WWII, for example, production of botulinum toxin to fill a British order took place in a tar-paper building dubbed "Black Maria," which was erected in 1944 and destroyed after the order was completed.[132] Construction at Fort Detrick, the central facility of the program, started in April 1943, but up until the end of WWII, it had only temporary structures. In addition, only laboratory-scale work and pilot-plant development were conducted during that period, primarily on anthrax and botulinum toxin. The first pilot plant at Fort Detrick was activated in October 1943 in a field hangar. Its second pilot plant for anthrax production became operational only in March 1944. The other two pilot plants for production of brucellosis and anti-plant agents were activated in January and February 1945. No large-scale production was carried out due to the absence of facilities for such work. Construction of the Vigo plant was completed in May 1944, but it was still being tested with simulant production when the war ended. Consequently, it never produced any infectious agents. Although Fort Detrick's pilot plant was able to produce anthrax to fill about five thousand bombs in response to Great Britain's WWII request, no production for American operational readiness took place during that period.[133] The 1950 report by the Committee on Biological Warfare indicated that the bioweapons program was seriously lacking in laboratory space, scientific equipment, and testing facilities, which prevented it from reaching its stated goals.[134]

Permanent infrastructure for the bioweapons program was accomplished in the 1950s only when an outpouring of funding spurred by the Korean War permitted the expansion of the program's infrastructure. For example, construction of Fort Detrick's one-million-liter test sphere started in 1949 and was completed in 1950. Between 1950 and 1956, three additional pilot plants were established at Fort Detrick, along with several laboratories to conduct research in aerobiology, safety, medical science, viruses and rickettsiae, and bacteriology. Construction of the Pine Bluff production plant started in February 1951 and was completed in 1954. Large-scale production began the same year with the incapacitant agent *Brucella suis*, and the following year with *Pasteurella tularensis*, the causative agent of tularemia. Initially the plant was capable of producing only bacteria. Between 1964 and 1966, additional production capabilities were built at Pine Bluff to produce viruses, rickettsiae, and toxins, and to grow and infect mosquitoes with viral agents. Although some testing took place during WWII, large-scale open-air testing of infectious agents, as well as human testing of vaccines and other countermeasures, took place mostly in the 1950s and 1960s. And in 1962, the program's testing infrastructure was completed with the activation of the Deseret test site near Salt Lake City, Utah.[135] Hence, the bioweapons program achieved a complete research, production, and testing capability only in the late 1950s to early 1960s—almost two decades after the start of the program, and about a decade before it was terminated. These condition

prompted a group of Fort Detrick scientists and contractors to write a confidential memo to the head of President Kennedy's Science Advisory Committee, Dr. Colin MacLeod, complaining about the "vacillating and contradictory directives, excessive fluctuations in program emphasis," and noting that "creative scientists can operate effectively only in an atmosphere which allows a continuity of efforts."[136]

Meeting military requirements under these conditions proved difficult. What is striking about these developments is that they underscore the extent to which the military and political elites were out of sync with the actual state of the program. Under the pressure of international crisis, the armed services made operational plans long before the facilities required to support scientific, production, and weaponization work were completed. The program's ups and downs in budget allocation led to a situation in which facilities construction was always dragging behind military need. Making matters worse, the lack of coordination among the armed services led to multiple disruptions in scientific work, which in turn caused the program to have an extended knowledge accumulation phase. According to scientists at Fort Detrick, the knowledge accumulation phase lasted about twenty years—from 1943 to 1965—and it was only four years before the program's termination in 1969 that they felt that they had experimented enough with various pathogens and learned enough about their behavior to make significant progress.[137] This stands in stark contrast to the Manhattan Project, in which overall facility construction was smoothly synchronized with scientific work and completed within the time frame required to support scientific work. In addition, coordination among the different parts of the Manhattan Project was nicely orchestrated by General Groves.[138]

The U.S. program's split personality disorder suggests three important conclusions. First, it would be a mistake to base the assessment of a proliferating state's or terrorist group's ability to develop a serious bioweapons capability on only a review of its potential access to expertise and facilities, as is often the case today.[139] The U.S. program had access to a substantial pool of expertise and infrastructure, as it could reach out to elite academic institutions and industry in addition to its own in-house capabilities. Yet it failed to produce a working weapon that met military needs after twenty-seven years of operation.

Second, the impact of military and political elites on a program's progress should not be underestimated. Disagreements, lack of coordination, and moral misgivings among decision makers can have a powerful negative effect on a program's progress and achievements by creating disruptions in scientific work, extending the knowledge accumulation phase, and further delaying weaponization. It would be wise to keep this in mind and nurture such disagreements when identified in a suspected covert program.

Finally, the U.S. program operated under very unique circumstances. It was a secret but legal program, as it operated before the signature of the Biological Weapons Convention (BWC). Therefore, it could afford to maintain a certain degree of openness in its dealings with the outside world. This permitted the program to attract expertise and leverage the capabilities of many academic and commercial institutions to complement and expand on its own capabilities. Such comparative flexibility in dealing with secrecy also clearly benefited the organization and management of its scientific and production activities. Post-BWC covert programs do not have this luxury. Because of their illegality, such programs need to construct strong barriers with the outside world and impose tight restrictions on knowledge diffusion, which necessarily affects weapons development. This important finding will be explored in the next two chapters.

CHAPTER 5

The Soviet Bioweapons Program

Failed Integration

When the first American delegation visited the anthrax production plant in Stepnogorsk, Kazakhstan, in 1995, they were struck by the enormity of the place. Spanning a territory of two square kilometers, the plant was composed of more than fifty buildings. The main production building alone was almost two football-field lengths and contained ten 20,000-liter fermentors, each four stories high, capable of producing 300 tons of anthrax a year. The facility housed a unique indoor 300-cubic-meter explosive test chamber with a removable dome. A line of bunkers hidden under a hill, sporting thick metal doors and two-meter-thick walls, were used to fill and store bombs with the deadly agent. A crane mounted on a railcar could carry the weapons to a loading area.[1] Stepnogorsk came to symbolize the mammoth proportions of the Soviet bioweapons program. Estimated to have been ten times bigger and having lasted about thirty years longer than the American program, we can only imagine what this complex really accomplished. Although Soviet authorities claimed to have destroyed the country's bioweapons arsenal before the breakup of the Soviet Union, its remnants were impressive: dozens of large facilities, extensive collections of pathogens, and thousands of bioweapons experts.

For all of its sheer magnitude, however, the Soviet bioweapons program did not achieve the level of accomplishment that such size, longevity, and resources might imply. Although the Soviet program had access to tremendous brainpower and seemingly limitless resources, available evidence suggests that it was able to weaponize classical agents but that work on genetically engineered agents did not go beyond the research and development phase, in spite of being the program's focus during its last twenty years of existence. Aside from the enormous task of creating pathogens unavailable in nature, the outcome of the Soviet program is the result of a combination of negative variables—both endogenous and exogenous—aggravated by the added constraint of clandestinity. Indeed, although the Soviet program

mobilized much of the scientific community—tapping into a huge knowledge base to support its activities—the program's organizational and managerial characteristics did not allow it to exploit this knowledge for maximum output. Instead, the program's structural fragmentation and compartmentalization, together with its rigid autocratic management style, created numerous barriers to knowledge transfer. On the exogenous side, the program was hampered by political interference with scientific decisions throughout its lifetime and by the deficiencies of the Soviet economic system, which led to perturbations and delays in program advancement. Ultimately, however, the program was crippled by the need to ensure its covertness after Soviet authorities signed the Biological Weapons Convention (BWC) in 1972. Whereas the challenge of creating new pathogens required a greater level of system-wide integration, cooperation, and knowledge sharing, the illicit character of the program imposed extreme secrecy and increased segmentation due to the risks of detection. The net result was a program that failed to integrate its disparate resources into desired bioweapons outputs.

Program Overview

The Soviet bioweapons program was the longest running and largest program ever conceived and executed. Although its origins date back to the late 1920s, it arguably did not reach its apogee until between 1972 and 1987. A period of contraction occurred in the late 1980s, during the Gorbachev era, and the program officially ended in 1992, when President Yeltsin signed Presidential Decree No. 390 in April 11, 1992, abolishing the entire program and officially recognizing that the Soviet Union had sustained a covert bioweapons program despite having joined the BWC in 1972.[2]

During its sixty or so years of existence, the Soviet program resulted in a vast infrastructure, composed of dozens of research institutes, production plants, and test and storage sites, and a workforce numbering in the thousands. It produced stockpiles of agents and munitions that considerably exceeded those of the United States. As early as the late 1930s, the Soviet program had an infrastructure that surpassed that of the American program, with half a dozen research institutes studying human and animal diseases, and three test sites.[3] After slowing down during the 1940s and 1950s, the Soviet Union vastly expanded the program in the early 1970s with the construction of new research and production facilities. Additionally, scientific and public health institutions, some of which were in operation before the creation of the bioweapons program, were enlisted to support weapons work. To wit, the anti-plague system (APS), which was established by Russian imperial authorities in the late 1800s to control the spread of endemic diseases, was drawn into the bioweapons program in the late 1960s. The Soviet military viewed the APS's decades-long experience isolating and working

with the causative agents of dangerous diseases (plague, tularemia, anthrax, cholera, hemorrhagic fevers, and others) as a resource they could exploit to advance bioweapons work and design preventive measures.[4] A network of veterinary institutes researching animal and plant diseases was also added to the bioweapons complex to develop anti-animal and anti-plant bioweapons.

Spanning across multiple jurisdictional boundaries, the Soviet bioweapons complex was composed of three concentric circles of facilities. At the center of the complex were an estimated thirty facilities under the authority of the Ministry of Defense (MOD) and Biopreparat—the flagship of the revived bioweapons program, created by decree in the early 1970s to conduct offensive bioweapons work under the guise of pharmaceutical research and production. The second circle comprised facilities that actively contributed to the offensive and defensive bioweapons programs but also maintained a genuinely civilian activity, such as the APS, which was simultaneously involved in disease surveillance and bioweapons work. Many of these facilities were placed under the authority of civilian agencies, such as the Ministries of Health and Agriculture, and the Academies of Sciences and Medical Sciences. The third, and largest, circle encompassed research institutes that made passive contributions to the bioweapons program by providing agents and research findings that were not specifically conducted for bioweapons purposes but that could support the bioweapons program. A special office of the KGB was created in all of these facilities to transfer research findings of interest to the military. The number of facilities falling under the last two circles is difficult to estimate; however, it is reasonable to believe that they numbered more than fifty. The APS alone was composed of about one hundred facilities in Soviet times, with at least two dozen directly involved in the bioweapons program.[5]

Soviet authorities also built redundancy into the infrastructure of the bioweapons complex by creating "sister" facilities in different parts of the Soviet Union, with similar research projects, to ensure continuity of work should any critical part of the program be destroyed during a war. To ensure rapid mobilization in wartime, several mobilization facilities were created and completely equipped to produce industrial quantities of pathogens. In peacetime, they were staffed with a minimum number of employees, who would be supplemented with additional personnel if the facility were activated to meet the war effort.

To prevent detection and provide plausible deniability, Soviet bioweapons facilities were designed to have civilian components that served as a cover for their military activities. The civilian cover was located at the same site as the bioweapons facility, but it had separate buildings and a dedicated staff, who did not mix with bioweapons employees or contribute to military work. For example, the biopesticide production plant, called Progress, was collocated with the anthrax production plant at Stepnogorsk to serve as a

cover for the bioweapons facility.[6] To further prevent detection by satellite imaging, when feasible, bioweapons facilities were designed to resemble a hospital complex, surrounded by gardens, where people walked around in what looked like pajamas—a shirt and pants outfit that comprised the standard lab coat in the Soviet bioweapons complex.[7]

The total number of employees in the bioweapons complex is often estimated to have been between 30,000 and 60,000, roughly an order of magnitude larger than the U.S. program. These numbers, however, are misleading because they include *all* of the individuals employed in the bioweapons program, from janitors to senior scientists, as well as the civilian cover. Some government reports provide more conservative numbers, with an estimated 15,000 Soviet specialists who possessed bioweapons knowledge and skills.[8] The real number is probably lower than that, considering that the number of scientists and technicians with bioweapons expertise in each facility varied greatly, in some cases representing 80 percent of the staff, while in others, no more than 10 percent. For example, the bioweapons production plant at Berdsk, Russia, was mostly a scientific and engineering site, with about 80 percent of its 150 personnel composed of scientists, and a very small support staff. In contrast, a sister production plant in Omutninsk, Russia, had approximately 350 employees, consisting of almost an equal number of support and scientific personnel.[9] Similarly, the anthrax production plant in Stepnogorsk employed about 4,500 people in Soviet times, with only about 900 involved in the bioweapons portion of the plant's activities. Among these, only about 300 were individuals with bioweapons expertise—less than 10 percent of the total staff.[10] In spite of the challenges in providing exact figures, we can safely say that the number of personnel with bioweapons expertise in the Soviet program far exceeded comparably trained staff in the American program by at least a few thousand individuals.

Interviews with former Soviet bioweapons scientists indicated that the bioweapons program never suffered from a shortage of funding. Exact budget figures, however, are hard to come by. Due to the Soviet practice of funding its defense sector by combining open and hidden budget allocations, budget estimation is a challenging task. Moreover, when the program became illicit after the signing of the BWC in 1972, funding sources were most probably of the hidden kind. The dispersion of the bioweapons complex across various agencies also implies that its total budget needs to be reconstituted by estimating its value within each of these agencies' budgets—a task impossible to accomplish without access to currently unavailable official documents. Nonetheless, available data can help assign a very approximate value to the bioweapons program. In his memoir, Ken Alibek indicates that in 1990, as Gorbachev was imposing defense budget cutbacks, the funds allocated for bioweapons work were close to $1 billion.[11] In early 1989, Gorbachev announced a military budget of $46 billion, but Western authorities estimated it to be about twice this amount, or about $92 billion.[12] This

would place the bioweapons program at about 1 percent of the defense budget, which does not seem to be an overestimation. If we assume that the annual bioweapons budget was indeed $1 billion and that it increased to $1.5 billion during the first ten years of the expansion phase, due to the construction of new facilities and the acquisition of modern equipment, the total budget for the program over its last twenty years (1972–1992) could have plausibly amounted to about $35 billion. This rough estimate does not include the budget allocated to the civilian components of the bioweapons facilities, nor does it include funds disbursed to facilities that passively contributed to the bioweapons program. Also not included are the funds invested in the program prior to the expansion of the bio-complex in the early 1970s. This is, nonetheless, a sizable budget, particularly when compared to that of the U.S. bioweapons program, which received about $700 million over a period of twenty-seven years.

The program's achievements are equally difficult to illuminate, due to the program's extreme secrecy and compartmentalization. Importantly, Soviet authorities reportedly destroyed the country's bioweapons before the Soviet Union's breakup in 1992, allowing no outside confirmation of their existence, let alone their quantity or quality. Nevertheless, interviews with defectors and scientists still working at former bioweapons facilities in the former Soviet Union support the conclusion that only meager results were achieved, in spite of the program's magnitude.

Interestingly, the achievements of the Soviet bioweapons program up to the early 1960s were very similar to those of the American program, even though the Soviet program had almost a two-decade head start. Until WWII, Soviet scientists worked primarily with natural strains of microorganisms and weaponized at least eight agents: *B. anthracis* (anthrax), *F. tularensis* (tularemia), *Y. pestis* (plague), *Coxiella burnetii* (Q fever), *Brucella suis* (brucellocis), VEE (Venezuelan equine encephalitis), botulinum toxin, and variola virus. They also designed several dissemination systems for these agents, including spherical bomblets, cluster bombs for delivery by aircraft, and spray tanks carried by medium-range bombers. There is no evidence, however, that they had developed a dedicated ballistic or cruise missile by this point.[13]

Like their American counterparts, Soviet scientists achieved several public health discoveries during the first phase of the program. For example, in the early 1940s, the Kirov institute—then the main bioweapons facility under the MOD—developed several new vaccines, including the first live vaccine for anthrax, which is still in use today in Russia. In 1941, Kirov scientists also developed a dried live plague vaccine, based on a *Yersinia pestis* strain obtained from the Pasteur Institute in Paris. The drying technique was a particularly important achievement; at the time, the liquid form of the plague vaccine did not survive more than ten hours at room temperature. The same technology was later used to develop dried live vaccines against tularemia, brucellosis, and tuberculosis, and was then transferred to the Ministry

of Health in 1946 for wider civilian use. Aerosol delivery of vaccines followed, which produced fewer side effects and allowed the immunization of troops under field conditions.[14] In 1944, the Kirov institute developed a method to produce penicillin in large quantities.[15] Two other MOD institutes at Sverdlovsk and Zagorsk developed antitoxins to protect against botulism, tetanus, and gas gangrene, as well as oral vaccines against smallpox and encephalomyelitis, and methods to cultivate anaerobic bacteria and diagnose several infectious diseases.[16]

After the expansion of the program in the early 1970s, Soviet authorities tasked the bioweapons complex to move beyond the natural strains of the first phase and develop new agents with no known treatment and strains that were antibiotic resistant or immunosuppressant. However, this second phase of the program seems to have been less successful at reaching its stated goals, despite the huge increase in its funding and size. It did make some scientific headway, but very little progress in weaponization.

On the scientific side, Soviet scientists reportedly conducted research on over fifty agents causing human, animal, and plant diseases. They also studied peptides with psychogenic or neurogenic effects, and explored the development of chimeric viruses, which combine agents causing different diseases, where the treatment of the first disease triggers the onset of the second disease.[17] Although some scientists made great scientific strides, much of their work did not go beyond the exploratory or development phase, achieving only a small portion of the research objectives defined by Soviet authorities. For example, the All-Union Research Institute for Applied Microbiology, in Obolensk, Russia, was tasked to develop pathogens resistant to ten antibiotics. The scientists were not able to reach that goal, but they nonetheless designed strains of *B. anthracis, F. tularensis, B. mallei*, and *B. pseudomallei* engineered to resist several antibiotics. They also attempted but failed to create a strain of plague bacteria resistant to antibiotics.[18] This work, however, was completed successfully at another facility—the Institute of Ultra-Pure Biological Preparations, in St. Petersburg, Russia—by Vladimir Pasechnik, who defected to the United Kingdom in 1989. The strain of plague Pasechnik developed was resistant to temperature extremes and to sixteen antibiotics. It is worth noting, however, that the development of this plague strain took twenty years to achieve.[19]

Other cutting-edge research included the modification of the antigenic structure of an anthrax strain, which masked the presence of the bacilli in the body, thus sharply decreasing the efficiency of vaccines and other countermeasures. Soviet scientists also genetically engineered a strain of *Legionella pneumophila*, which was designed to cause the immune system to attack nerve cells, precipitating a fatal outcome.[20] Although scientists at Vector experimented with the development of a smallpox chimera, available data suggests that they succeeded in introducing a gene of VEE into vaccinia (a usually nonvirulent relative of the smallpox virus), but there is no evidence

that they succeeded in replicating the experiment with the smallpox virus, or that they conducted any tests with engineered strains.[21] According to former bioweapons scientist Igor Domaradskij, similar efforts to develop genetically enhanced bio-agents against plants and animals were largely unsuccessful.[22]

Other achievements during the second phase of the program included the creation of automatic bomblet-filling machines, and the development of a large-scale production method for the anthrax bacteria and the smallpox and Marburg viruses. However, whereas large-scale production and testing of the anthrax weapon was taking place at Stepnogorsk by the late 1980s, the Marburg virus was only tested at Stepnogorsk during the same period, with no production taking place.[23] The production of smallpox was due to take place in a dedicated plant at Vector, but the plant's construction, started in the late 1980s, was interrupted by Gorbachev's cutbacks and never completed. More importantly, none of these strains were genetically engineered.[24]

Based on an admittedly incomplete picture, Soviet weaponization developments appear to have been limited. In their history of the Soviet bioweapons program, Milton Leitenberg and Raymond Zilinskas concluded that the Soviets probably did not load SS-18 ballistic missiles with smallpox, as previously declared by Soviet defector Ken Alibek. According to a former Soviet missile developer, one reason these efforts were probably unsuccessful was that a warhead filled with bio-agents would be much lighter than a nuclear payload and would thus require extensive modifications to its missile. Leitenberg and Zilinskas also indicate that although the Soviets attempted to develop a bioweapons warhead for ballistic missiles, as well as a dedicated land-attack cruise missile, their work did not go beyond the research phase. Leitenberg and Zilinskas also found no evidence that the Soviets resolved important technical problems associated with the delivery of bio-agents by ballistic missile: namely, ensuring the survivability of the agent during atmospheric reentry, when the stress of heat and speed could destroy the agent, and releasing it evenly at high speed.[25] It is worth noting that ballistic missiles face other challenges in effectively delivering biological agents. Their high velocity makes it difficult to adjust the pattern of agents they release according to wind direction and target shape. More flight-stable aerodynamic systems, such as land-attack cruise missiles, have been shown to create lethal areas for a given quantity of biological agent at least ten times larger than that of ballistic missiles, even when the latter employs submunitions.[26]

Although the Soviet program clearly surpassed U.S. bioweapons achievements, the results do not seem commensurate with the program's longevity; the size of its infrastructure; and the enormous financial, human, and material resources devoted to its objectives. Like its American counterpart, the Soviet program had greater successes in the science field than with weaponization.

The vast expansion of the program in the early 1970s does not seem to have moved the Soviet arsenal beyond the bombs and spray tanks developed during its first stage.[27] And much of the research launched during its last two decades did not progress beyond the exploratory and R&D phases. The elephant in the room, of course, was the enormity of the task: creating new agents with characteristics unknown in nature and controlled efficacy, together with effectively weaponizing them, was an ambitious objective that could not be easily achieved. No less daunting was convincing military users that such weapons could achieve predictable results, notwithstanding uncertain operational environments.[28] Yet considering the knowledge accumulated since the late 1920s, and the sheer size of the effort, such modest results seem surprising. A closer analysis of how the Soviet bioweapons program organized and managed science, and how the economic and political context affected scientific progress, arguably permits a better understanding of the obstacles that Soviet scientists faced in making significant progress in bioweapons development, particularly during the second phase of the program.

Knowledge Base, Organization, and Management

From its inception in the late 1920s, the Soviet bioweapons program had access to an exceptionally large knowledge base. Most of its staff in the early years of the program came from top-level research institutes and universities established prior to the Bolshevik Revolution, such as Moscow State University and the Moscow Institute of Epidemiology and Microbiology.[29] The program also benefited from expertise developed under the preexisting chemical weapons program, particularly in the field of chemical dispersion, which reportedly proved useful in understanding bio-agent dispersion.[30] After WWII, Soviet scientists gained new insight from German and Japanese scientists, including information about Japanese human testing, and according to Ken Alibek Japanese industrial blueprints influenced the design of the anthrax production plant at Sverdlovsk. Also of value were German industrial techniques and manufacturing equipment for large-scale production.[31] Further enriching the knowledge base, the expansion of the program in the 1970s mobilized much of the scientific community and brought into its structure research institutes with decades-long expertise working with agents of bioweapons interest, such as the APS. Finally, due to its priority status in the Soviet economy, the bioweapons program could pick the best university graduates to renew its staff throughout the postwar era and until the end of the program in the early 1990s.[32]

With such a vast knowledge base, one would assume that over the years, the bioweapons program was able to add layers upon layers of expertise to support the challenging task of creating new agents unknown in nature when the order to do so was given in the early 1970s. Yet an examination of

the program's organization and managerial characteristics shows that they severely impeded knowledge creation and transfer.

ORGANIZATION: FRAGMENTED ASSEMBLY LINE

One of the most striking characteristics of Soviet program organization is that it is the complete opposite of what is required to use knowledge efficiently. Structurally, the bioweapons complex was fragmented and compartmentalized. Special care was devoted to creating tangible and intangible distances between people by scattering facilities at various remote locations throughout the Soviet Union, and by constraining exchange between people via the use of multiple security clearances. In addition, the program had no system-wide integrative or coordinating mechanisms, and was also closed to the outside world. These organizational choices were consciously made by political authorities to limit individual knowledge of the program and to ensure its covertness. But they ultimately constrained the use of the expertise available at various institutes, prevented the institutionalization of knowledge, and frustrated innovation.

The Soviet complex had what I call an "assembly line" organization, in which specialization and fragmentation of tasks were reinforced by compartmentalization to ensure confidentiality of the program. From the structural point of view, the bioweapons complex was scattered and subordinated to a dozen government agencies.[33] Typically, one agency would not be aware of how many and precisely which facilities were under the control of another agency. The overall complex was composed of specialized facilities that conducted specific tasks and worked on a specific set of agents. Research was separated from production, and work on viruses took place at facilities distinct from those working on bacteria. Similarly, research on animal and plant diseases was separated from research on human diseases. Even testing on Vozrozhdeniye Island was fragmented: teams from different institutes came on a rolling basis to conduct their own experiments. This organization restricted the flow of information both within and between facilities comprising the bioweapons program, and stifled knowledge creation and transfer.

Fragmentation was also a characteristic of research projects, which were code-named and divided into multiple parts, the completion of which was entrusted to different institutes, often reporting to different agencies. Typically, participating institutes did not know which other organizations were involved in their overall project, and often were not aware of the purpose of their work. Although a MOD institute generally integrated the results of disparate work, very few facilities had direct contact with their "client." Instead, intermediaries were designated to serve as buffers between MOD facilities and the rest of the complex. For instance, within the anti-plague system, the Mikrob institute was a main point of contact for the ministry of

defense. Although this type of structural organization is well suited for industrial production, it is not favorable to knowledge production and transfer, and prevents cross-fertilization of knowledge.

These constraining features were also present within facilities where fragmentation and compartmentalization were achieved by using different levels of security clearances. Because teams of scientists included people with different clearance levels, exchanges of information were severely constrained among individuals working on the same project, which added another obstacle to knowledge creation and transfer. For example, in facilities where military and civilian scientists cooperated, military scientists usually had access to information denied to civilian scientists.[34] As noted in chapter 3, the divide between military and civilian scientists was a particularly obstructive factor during the scale-up of the smallpox weapon at Vector. Similarly, differences in security clearances led the KGB to redact the scientific protocols sent from the military facility at Kirov to Stepnogorsk in support of the anthrax weapon scale-up, which contributed to a two-year delay in anthrax production.[35] Distinctions between military and civilian scientists were also an impeding factor in the development of a large-scale production process for the smallpox weapon, as civilian scientists at Vector were allowed only limited access to the protocols fully accessible to their colleagues dispatched from the military facility at Zagorsk.

Compartmentalization and secrecy also adversely affected information transfer and cooperation between facilities. For example, Vector scientists were tasked to weaponize the Marburg virus, but they received no support from military scientists at the Zagorsk facility, who had about a decade of experience working with the virus.[36] Vector scientists had to reinvent knowledge that already existed in another part of the bio-complex, leading to substantial delays in achieving the desired results.

The closed character of the Soviet bioweapons complex, in which scientists were not allowed to publish or attend open conferences, further limited information exchange and the enrichment of resident knowledge. Scientists generally attended only secret meetings and conferences, and published primarily in secret journals, while Ph.D. candidates at bioweapons facilities defended secret dissertations before closed committees.[37] In addition, bioweapons facilities could not exploit the expertise available at civilian organizations or universities because direct interactions with such organizations were not permitted. If outside expertise became essential either within the bioweapons program or in the civilian world, a cover story had to be developed for the scientist seeking support in order to avoid disclosing the purpose of his inquiries or visit.[38] Visits at bioweapons facilities under the control of the MOD were even more strictly regulated, requiring official authorization from the MOD.[39] For example, Igor Domaradskij faced tremendous difficulties receiving authorizations to involve anti-plague scientists with knowledge about tularemia to support his work on a tularemia

weapon at Obolensk.[40] Even in the event of disease outbreak, bioweapons scientists could not provide information to public health system representatives to help respond to the outbreak. As one scientist recalls:

> We had done very important research; we had diagnostics that we could not transfer to the public health system. Even the fact that there was a plague outbreak could not be revealed. And it was awkward not being able to tell a physician standing next to me "this is a case of plague." We had to make a fake diagnosis.[41]

The obstacles to information transfer from the bioweapons field to the civilian sector were compounded by restrictions imposed by authorities in the various Soviet republics. For instance, the Soviet Republic of Uzbekistan imposed a blackout on information about certain disease outbreaks, such as cholera. These authorities feared that central authorities in Moscow would see acknowledging such outbreaks negatively. Such blackouts redounded to the disadvantage of unwarned neighboring republics, where the disease would frequently spread. An anti-plague scientist from Kazakhstan indicated that the only way to confirm an outbreak originating in Uzbekistan was to call their Uzbek colleagues, and if they were "out of town," it probably meant that they were responding to the outbreak.[42]

Secrecy also imposed certain reporting practices that further limited information transfer. Because the secret reporting procedure was highly cumbersome, scientists ended up writing very little in official reports and mostly transferring their knowledge to their colleagues while working together in the laboratory on a common project. This limited the spread of knowledge among groups of scientists in various parts of the program, and reduced their ability to learn from one another.[43] A former Soviet scientist describes the secret reporting process as follows:

> That was a very complicated process. . . . We could write only on blank sheets of paper provided to us by Department #1 [KGB]. . . . The requirement was to sit in an empty room, at an empty desk, with a pen and a blank piece of paper, . . . nothing else was supposed to be on the desk, except these forms. So everybody tried to avoid it because it excluded any scientific process: you always have something on your desk, you refer to, you read, you think, you synthesize. And if you make notes in the BSL 3 or 4 facility, then to bring out the notes was a pain. . . . The notes were written on a piece of paper with a pencil, then the paper was decontaminated and after the decontamination solution, the paper was . . . extremely difficult to read. The notes were essentially in the memory. People memorized a lot and then described. Sometimes they would use pieces of paper to put notes in cryptic language.[44]

Thus, in the absence of mechanisms for information exchange, the Soviet bioweapons program proved to be an assemblage of noncommunicating

reservoirs of knowledge. With no functional overlap built into the system, the tacit knowledge available in parts of the program could not be transferred to those who needed it to solve scientific or weaponization problems. The absence of lateral linkages between stages and facilities reinforced the sequential character of bioweapons work and prevented cross-pollination of knowledge. In addition, the absence of coordinating and integrating functions to synchronize interdependent tasks and people fostered numerous delays and compromised the successful completion of projects.

Ironically, the KGB, which had an office in each facility, was the only formal mechanism of knowledge transfer within the bioweapons complex. Its role was indeed to forward research results produced in a variety of institutes to the military to support bioweapons work. But because it performed this task covertly, without involving the authors of the scientific results, it merely served as couriers of incomplete information, which prolonged the completion of bioweapons work. In his memoirs, Igor Domaradskij laments that the military used his work on plague, without reference, to develop a strain of plague resistant to antibiotics. Domaradskij's work was first transferred to Kirov, which failed to produce the antibiotic-resistant strain. His work was also likely forwarded to the Institute of Ultra-Pure Biological Preparations, where Pasechnik eventually succeeded in producing the strain. But it took twenty years to achieve this result—an accomplishment that arguably could have been achieved much faster had the teams involved coordinated their efforts.[45]

The scientists who were at the end of the assembly line were responsible for integrating the disparate pieces of work produced by different entities. But they were not system integrators per se, because (1) they did not interact directly with the scientists who performed these tasks; (2) work was accomplished at facilities subordinated to different agencies that did not necessarily have the authorization to call on these scientists; and (3) government agencies tended to compete with one another rather than cooperate. More importantly, with such a fragmented system, problems could not be identified early on in the development process; instead, they were often discovered at too late a stage to identify the source or resolve the problem.

CENTRAL AUTOCRATIC MANAGEMENT

Central autocratic management reinforced the negative effects of the Soviet bioweapons program's organizational characteristics. Put simply, the bio-complex was managed as a vertical military organization, where decisions were made at the top with little participation from lower echelons. This rigid decision-making process resulted in a management out of touch with scientific realities. Although some facility managers attempted to introduce within the walls of their institutions a greater level of flexibility, encouraging cooperation and information sharing, the fruits of their inter-

ventions could not spread to the rest of the complex due to its overall compartmentalization.

Production and research objectives for the bioweapons program were determined by federal authorities in Moscow, namely the Central Committee of the Communist Party and the Military Industrial Commission (VPK), on the basis of a five-year plan. These objectives were then directed down to the research organizations and production plants via their reporting authorities, such as Biopreparat, with the task of defining the intermediate stages required to reach these objectives. These work plans were then sent back to the top echelons in Moscow to be included in the five-year plan. Once the plan was adopted, it had to be accomplished, and the set objectives and intermediate stages could not be modified.

Former Soviet bioweapons scientists indicated that the objectives set by Moscow were unrealistic or too ambitious for a five-year period. Because very few apparatchiks within the central authorities had a scientific background, they rarely measured the level of complexity of the tasks they assigned. In addition, top-level bureaucrats at reporting facilities, such as Biopreparat, often made matters worse by promising greater results than those requested by the central authorities, to advance their careers.[46] Some were too removed from the realities facing bench-level scientists and also contributed to the imposition of unrealistic goals.[47] The consequences of such top-level direction were profound. At the facility level, scientists developed annual plans that could conceivably be fulfilled, but only if they were able to acquire the necessary material inputs and resources to achieve such a plan. More often than not this proved impossible due to the deficiencies of the Soviet economy. Procurement problems aside, scientific plans at times needed alterations, due to unexpected scientific contingencies. However, such a course of action could not be pursued, even on the basis of valid scientific reasoning, because deviations from the plan bore heavy consequences. In the Soviet system, entities that did not accomplish their assigned portion of the plan faced sanctions, ranging from the removal of their leader to the allocation of fewer material, human, and financial resources in the next five-year plan. As a result, no manager at bio-facilities or reporting authorities (Biopreparat and others) wished to consider an option that would dissatisfy and thus engender the wrath of the central authorities. As a former bioweapons scientist observes:

> The essence of the problem was that the small peptides expressed by microbes had to provide new properties for these microbes. But it turned out that it was very difficult to express these small peptides as isolated molecules; it was much better to fuse them with bigger carrying molecules. . . . Scientifically [using bigger molecules] did not change much, but bureaucratically [it was not acceptable, because] these were not isolated peptides [as indicated in the plan]. . . . In order to change that requirement, Biopreparat

> had to explain to the Central Committee of the Communist Party why that peptide had to be fused with bigger protein. . . . Biopreparat wanted to avoid it. . . . They put enormous pressure [on us] to keep the scientific research according to the directions of the Communist Party.[48]

By preventing scientific institutions from making scientifically justified changes in their research approach, the central authorities also prevented them from exploring other, possibly more successful, research avenues, thus further constraining their ability to meet the set objectives.

Interviews with former Soviet bioweapons scientists indicated that some managers at the facility level played an important role in mitigating the characteristics of the Soviet organizational structure and managerial characteristics. Two models of managerial intervention emerged. On the one hand, some directors strived to flatten the structure of their institution by relaxing compartmentalization and security requirements, thereby encouraging collaboration and information exchange. On the other hand, other directors strictly echoed the Soviet organizational structure and management style within their facilities, thus preventing the efficient use of knowledge. Not surprisingly, the flatter structures were more successful in solving their technological challenges. Although the military managers tended to favor vertical structures, the personality of the directors seems to have had greater influence in shaping the corporate culture of an institution than their having been part of either a military or a civilian community.

For example, Vector's director, Lev Sandakchiev, was able to create a cooperative environment within Vector by encouraging collaboration and information sharing among personnel. Sandakchiev originally came from the academic world, and when he assumed his functions at Vector, he brought with him many of his colleagues and students from the Novosibirsk State University. This academic background was a contributing factor to his management style, which emphasized openness and exchange rather than secrecy and fragmentation. One of his strategies was to organize regular meetings in which laboratory heads could present their projects and discuss the difficulties they faced with their colleagues. This allowed collective problem solving and the contribution of various parts of the facility to the overall technological objective.

To motivate his staff to achieve faster results, Sandakchiev designed several types of incentives. One of them was to give scientists resources to work on issues that were of interest to them, provided they made progress in their bioweapons work. He also made it a point to mentor junior scientists, and encouraged innovation and the development of new ideas. Another strategy was to create an internal competition system, by which he would task two teams with the same project. A young but promising scientist would head one team, while an accomplished scientist would

lead the other, and the more productive team (or individual) would receive higher compensation in the form of bonuses and other perks that a director could distribute, such as priority position on the list of people who could buy cars—a rare privilege in the Soviet Union.[49] This internal competition, however, had negative side effects, because it resulted in placing bench scientists and technicians under multiple subordinations—their laboratory head and a competing principal investigator (PI), for instance—thus creating conflicts of interests and potential confusion. Nevertheless, scientists who worked at Vector viewed it as an efficient way to create a positive-incentive mechanism within the context of the Soviet system.[50]

Whenever possible, Sandakchiev also broke the isolation of his employees by encouraging exchanges with other institutes, sometime sending them overseas, where they could acquire new knowledge. Former Vector employees indicated that Sandakchiev made it clear that fundamental science was more important than bioweapons work, and encouraged them to learn as much as possible. Some scientists were even able to avoid working on bioweapons projects entirely. A former scientist explains how Sandakchiev dealt with the bioweapons program:

> Sandakchiev always . . . provided minimal amount of resources to do stupid [bioweapons] experiments, and the rest of the resources went somewhere [else]. . . . And actually I believe he was politically so good, that his bosses also understood it. So they did the absolute minimum to meet the requirements of the military projects. And the rest [of their activities were devoted to] academic development, development of new projects, some new ideas and whatever was allowed. And only when it became a very critical point, he [would] deliver something with regard to these military projects. . . . He always told people [bioweapons work] is all garbage, nobody wants it, nobody needs it. But since they [MOD] pay for this, we have to do it [but] we have to do very, very little. That was the whole atmosphere in the institute.[51]

Undoubtedly, this would have been more difficult to achieve had Sandakchiev not been a member of the Academy of Sciences, which provided him with substantial political clout. Yet his methods were quite successful in limiting the effects of the Soviet organizational model on scientific achievements at the facility. Because of his unorthodox managerial interventions, he was able to connect the various knowledge reservoirs for maximum efficiency. And given that he served as Vector's director from its inception in the mid-1970s to his passing in 2006, he was able to maintain a culture of relative openness and ensure the stability and continuity of work over a long period, which benefited the institutionalization of knowledge. Indeed, even though Sandakchiev allocated only a small portion of his resources to complete bioweapons work, his interventions created a more flexible organization, able to use and create new knowledge and adapt to new challenges.

Not surprisingly, Vector became one of the most innovative organizations of the bio-complex.

Other organizations within the Biopreparat system were similarly managed, in spite of the fact that their managers were from the military. For example, Ken Alibek, who held the rank of colonel, created a similarly open intellectual environment at Stepnogorsk. He relaxed security clearance rules in order to allow the staff to exchange information more freely. As Alibek notes:

> When you talk about science and technology you cannot keep everything separate. If you provide only the necessary information, you can get into trouble. . . . In our facility everything was interconnected . . . so it would have been stupid to impose any secrets between different departments, divisions and labs.[52]

Another critical managerial decision was to ensure personnel mobility and do without a discipline-based division of work. Instead, work relied on interdisciplinary teams that worked together to solve the challenges of scaling-up anthrax, bringing together individuals working in the research, production, and weaponization sides of the facility. In other words, Alibek established a functional overlap, allowing the collective resolution of problems associated with upstream and downstream stages of a weapon's life cycle. In addition, personnel mobility and exchanges occurring within the facility supported the development of a transactive memory, allowing staff to call on colleagues who had the appropriate expertise. Interdisciplinary teams of ten to fifteen people even conducted open-air testing at Vozrozhdeniye Island.[53] A former Stepnogorsk scientist describes Alibek's management style as follows:

> He had an intelligent, open-minded approach to problem solving, and an unusual way of defining and implementing tasks. . . . The scientific personnel at Stepnogorsk responded very well to his management style and produced high-quality work on time. As for me, I enjoyed much more working at Stepnogorsk than at my former [MOD] organization.[54]

A counterexample is the case of the Obolensk facility, headed by General Nikolai Urakov. Although it was part of the ostensibly civilian Biopreparat system and had among its staff few civilian scientists, Obolensk was primarily staffed with military scientists and was run like a military organization. Urakov originally came from the MOD facility at Kirov, where he served as deputy director. Scientists who served under his direction indicated that he imposed a strict military discipline and hierarchical rules. He also strictly replicated the Soviet compartmentalization and fragmentation

of scientific work. Scientists could not cooperate or discuss their respective work unless they contributed to the same research project and had the required security clearances. Former Obolensk scientists indicated that they had no knowledge of the work done in other labs within the institute, and they had no internal meetings discussing their respective work. They also reported that Urakov did not want to deviate from the plan; he pressured his scientists when they could not reach the assigned objectives. Accordingly, he requested from lab heads daily progress briefings, and the pressure trickled down the hierarchical ladder, creating an oppressive work environment filled with conflicts. Scientists also reported that the strict adherence to hierarchical rules inhibited the development of new ideas. Thus, junior scientists who wanted to innovate were discouraged by their superiors and asked to limit their work to implementing the tasks assigned to them.[55]

Because Urakov exerted substantial influence on his staff members' careers, most were disinclined to question their assignments and typically limited their work to the strict specification of the plan, even when they knew it made little scientific sense. This created numerous conflicts between civilian and military scientists within the organization, each group having different ways of approaching scientific problems. A former civilian scientist from Obolensk recalls:

> The person next to you may have been involved in the same project, but the approach was different simply because his commander ordered him to do it a certain way. And you approach the person and discuss the problem, and [he] would say, "I cannot do it differently; scientifically it makes no sense, but it does not matter because my boss, my commander, placed an order. I cannot disobey."[56]

The lack of scientific freedom, coupled with the absence of encouragement from management, created a very gloomy work environment, which had a direct impact on productivity. A former scientist recalls:

> The absence of the feel that in the future, it'll get better . . . you'll get promoted, you'll discover something interesting . . . typical things that motivated people, were absent. Some people dreamed about retirement; it was interesting to see people in their late 30s dreaming about retirement, because they could retire at 40–45. . . . They were just exhausted people in their early ages; they were thinking of getting rid of it, as much as possible, by any means. If I'm ordered to do something, I'll do it by any means. I won't think about it . . . I won't create anything . . . I'll just serve my duty.[57]

To make matters worse, the layout of the laboratories at Obolensk also served to decrease morale among its scientific personnel. Most buildings were temporary one-story barracks made of wood and bricks, which

telegraphed the idea that no future expansion for more sophisticated and interesting research was planned. Obolensk had a large explosion chamber to test munitions, but that structure, too, was temporary. Building #1—Obolensk's main permanent research facility—was established only in 1984. At that point, some scientists moved into the building, while others remained in the barracks. In contrast, from the outset, Sandakchiev insisted on building a permanent infrastructure at Vector, which served as an additional motivating factor for personnel.[58]

Due to organizational rigidity, personnel at Obolensk primarily worked individually, which limited access to expertise available within the organization. Having served as director for about twenty years, Urakov created a corporate culture that emphasized rules and hierarchy, thus stifling innovation. Scientists who worked at Vector and Obolensk indicated that the facility limited itself to using old methods and making only incremental progress. Compared to Vector, Obolensk lagged far behind on various common projects. This is a telling outcome, considering that Vector scientists started with a handicap, having no bioweapons knowledge, while most Obolensk scientists came from military institutions, like Kirov, which had a long history in bioweapons work. A scientist who worked at both facilities explains the difference in outcome:

> Although there were some knowledgeable military people in place, and well-organized teams of people . . . the people in charge at Obolensk were from the previous generation. What we had at Vector was a lot of younger people without inhibition. And . . . when people are not inhibited, when they have free thinking, [it] moves people much further. . . . Many approaches taken at Vector could be considered as [having] no appropriate scientific background or maybe too naïve . . . but that allowed in many cases to take nontraditional, new approaches. In the long run this moved them further, than the classical, grounded system in Obolensk. After 5–6 years it became obvious that they [Obolensk] needed help to advance in a certain direction.[59]

This point underscores the importance of managers. By replicating the rigidity of the Soviet system, Urakov created stronger barriers between knowledge reservoirs, prevented the creation of transactive knowledge, and obliged scientists to rely exclusively on their more limited expertise, and that of their immediate collaborators. By making these choices, he failed to exploit his staff's starting advantage. Conversely, Sandakchiev and Alibek were able to obtain substantially better results by favoring the creation of communal knowledge and connecting their staff with communities of practice whenever possible, thus allowing for the cross-pollination of knowledge and innovation.[60] These managerial interventions, however, had their limits: the overall compartmentalization of Soviet weapons work still

hindered the optimal spread of such innovations throughout the entire Soviet bioweapons program.

Exogenous Factors

Further compounding the effects of endogenous variables, several exogenous factors further diminished the program's ability to institutionalize knowledge. A frequently overlooked characteristic of the Soviet bioweapons program is that it was subject to several disruptive political perturbations throughout its history. Political meddling with science reached catastrophic proportions during the first stage of the program, when Stalin's purges and his policy of Lysenkoism—named after Trofim Lysenko, who rejected the theory of evolution and genetics—effectively destroyed the program's knowledge base, creating a twenty-year hiatus in weapons development. Consequentially, the expansion of the program in the early 1970s had very little to rely on. The scientific base of knowledge was rudimentary, while the necessary infrastructure had yet to be built. As a result, the revival of bioweapons work was delayed by another decade, until the early 1980s, when the bioweapons program had sufficiently extricated the vestigial legacy of Lysenkoism; and laboratories, material, and equipment became available to support bioweapons work. By the late 1980s, as a result of Gorbachev's reforms, bioweapons work began to wind down. In other words, the Stalin era and its aftermath shaved about thirty years off the program's life span, giving Soviet scientists only about ten years to design new agents and weaponize them before the program ended in the early 1990s. Reaching this objective in a shortened time frame was in itself a Herculean task, but it also had to be accomplished in an economy characterized by a deficient supply system, which created additional delays and negatively affected the social context within the bio-complex.

PRIORITY AND POLITICAL INTERFERENCE

Because it was part of the defense sector, the bioweapons program received preferred status in the allocation of resources, access to foreign-origin equipment, and unlimited budgets. Its personnel enjoyed higher salaries than those of civilian organizations, 10 percent salary increases every year, options for early retirement, and other perks not available to other sectors, including larger apartments and subsidized groceries.[61] However, these seemingly ideal conditions did not always contribute to the creation of a work environment propitious to knowledge creation and improved scientific output. What much of the literature has failed to explicate adequately is the other side of the priority status coin: a pernicious political intrusion in scientific decisions and meddling in the way science was accomplished,

which resulted in delayed achievements and in corrupting a portion of the scientific community.

Political intrusion in scientific work was particularly acute during the Stalin era, when the biology community suffered successively from Stalin's purges and the policy of Lysenkoism. Starting in 1937, manufactured suspicions that the Japanese and German intelligence services had turned Soviet scientists led to the arrest and execution of hundreds of scientists, including several military and civilian microbiologists. Among them were some of the founders of the Soviet bioweapons program, such as military physician Jakov Fishman, and microbiologist Nikolai Ginzburg, who developed the first anthrax vaccine.[62] In 1939, Stalin placed all bioweapons activities under Minister of Internal Affairs Lavrenty P. Beria, who tightened the rope around the bioweapons program. Dozens of eminent microbiologists were arrested multiple times, exiled, executed, or sent to labor camps, where they worked on bioweapons as prisoner-laborers.[63] Beria also placed bioweapons work under tight scrutiny, requiring direct reports from facility directors. General Piotr Burgasov, a military bioweaponeer who lived through that era, indicated during a 2001 interview with *Moscow News* that Beria required from him monthly written reports about the program's progress, with a copy sent to Stalin. No other individual was to be informed of the program's work. During the interview, Burgasov recounted an incident in which after a field test he allowed one of his employees—also working for the KGB—to go home one day earlier than planned. Instead, the employee reported to his KGB superior and informed him about the test. When Beria learned about the transgression, he sent for Burgasov, who was reprimanded. Burgasov was close to Beria, which probably explains why he was not arrested or executed.[64]

While the purges continued to decimate the scientific community, Trofim Lysenko's doctrines had a more insidious and long-lasting effect on science. Lysenko, an agronomist by training, came to prominence due to his work related to the study of plant germination. His theory was that plant evolution was not defined by genetic makeup but by the environment in which plants evolve. Although Lysenko's work was criticized for its lack of scientific rigor and oversimplification, Stalin saw in the man and his theories a vehicle to promote the five-year plan and the collectivization of agricultural land, both launched in 1928. With Stalin's backing, Lysenko quickly rose in the ranks, becoming the head of the Academy of Agricultural Sciences and a member of the Academy of Sciences, which allowed him to extend his original theory of plant evolution to a general theory of evolution. From then on, modern genetics became heresy; eminent geneticists were persecuted, while others who feared for their lives quit the field or adopted a low profile. Teaching of modern genetics was altogether banned. Lysenko's deleterious influence on biology remained strong until 1964, when Nikita Khrushchev, his protector after Stalin, was removed from power.[65]

Further intruding on the scientific community, Stalin had himself and other Communist Party officials elected members of the Academy of Sciences and reportedly edited Lysenko's speech to the Academy of Agricultural Sciences, establishing Lysenkoism as the party line in 1948. Stalin also participated in the academy's scientific discussions about biology and genetics. Although similar discussions were organized in the field of physics, the increasing importance of the nuclear weapons program after the U.S. bombing of Hiroshima and Nagasaki ended this practice, diminishing political intrusion in nuclear development. In fact, Stalin and Beria showed unusual restraint regarding dissident views within the nuclear program and refrained from removing scientists who were viewed as essential by the program's senior managers. They also placed competent engineers and managers in charge of the industrial aspect of the nuclear program. Biology and the bioweapons program did not receive similar treatment. Adherence to the party line trumped competence. Several internal police officers were also secretly placed within scientific institutions, at times posing as graduate students. And in spite of their scientific incompetence, they and other Communist Party members received degrees in biology based on dissertations written by more competent scientists, thus creating a whole cadre of incompetent biologists.[66]

After Khrushchev's ousting, the scientific community began to take stock of the repressive years. Soviet science lagged behind Western science, particularly in molecular biology and genetics. It also lacked modern equipment and laboratory space to conduct advanced research. Little was achieved in the bioweapons field after WWII. Although Stalin had created two new research institutes in Sverdlovsk (1949) and Zagorsk (1953) and established permanent research and testing facilities at Vozrozhdeniye Island (1952), former Soviet bioweaponeer Igor Domaradskij claims that by the late 1960s, the military command was questioning the need to maintain the program, due in part to the successful development of nuclear weapons in 1949, which the military believed made bioweapons superfluous. According to Domaradskij, the military also viewed bioweapons as unreliable, due to the difficulty in controlling their dispersion and the possible risks of infecting Soviet troops. In addition, at the time bioweapons used only natural strains, making it easier for the enemy to develop countermeasures.[67]

It is important to note that although biological science suffered greatly during Stalin and Lysenko's reign, it did not collapse altogether. A few biologists continued to practice within the nuclear sector, under the protection of Igor Kurchatov—head of the nuclear weapons program—ostensibly conducting research in cybernetics.[68] Nevertheless, by destroying scientific talent and corrupting a whole generation with Lysenkoism, the Stalin era effectively created a twenty-year hiatus in the bioweapons program. It is not surprising, then, that in the 1960s, the Soviet program's achievements were very similar to those of the American program, in spite of the fact that the latter program started almost two decades later.

Political interference with scientific research did not end with Stalin's death. Instead, it persisted until the end of the program through the involvement of various political organizations within bioweapons facilities. All facilities had Communist Party and trade union representatives within their walls, which were responsible for promoting the party line, not defending employee interests. These organizations interfered with scientific decisions and the quality of work because they could disburse perks to those they favored, and they could affect a scientist's position or advancement.[69] In short, people who followed the party line were more easily promoted, irrespective of their performance or qualifications. Conversely, those who did not have connections or membership in Communist organizations or unions met obstacles in obtaining desirable positions, and could even be demoted or removed.[70] For example, one interviewee recalls that he was removed from his institute in Moscow because he rejected membership in the Komsomol—a Communist youth association—in the early years of his career:

> I was told, "There are no prospects for you here." . . . I started looking for another job, and for about two years I could not find anything because information about my "deficiencies" [rejection of Komsomol membership] preceded information about my achievements. . . . I tried everything; my only chance was an institute in Dushanbe [Tajikistan].[71]

The scientist eventually befriended an influential veterinarian from the Control Veterinary Institute in Moscow, who pulled some strings to bring him into her institute.[72]

At times, party apparatchiks from Moscow would interfere with an institute's personnel or work plan purely for political reasons. In his memoir, Igor Domaradskij recalls an episode involving Piotr Burgasov, who, soon after being appointed deputy minister of health in 1965, rejected Domaradskij's work plan and demanded Domaradskij's firing because a lab assistant had come down with anthrax. Eventually, however, he settled instead on replacing Domaradskij's deputy with a retired army scientist. Domaradskij surmised that the reason for Burgasov's attitude was that he viewed him as a threat, since both had been considered for the deputy minister position eventually offered to Burgasov.[73]

Hence, although the influence of political authorities in the post-Stalin years was not as drastic as it had been during the Stalin era, even during the expansion period, political organizations could negatively influence scientific decisions. Also, by removing competent personnel or promoting individuals on political grounds, political authorities also disrupted the continuity and stability of scientific work, which clearly and negatively affected the program's achievements.

DELAYED EXPANSION

Another overlooked aspect of the Soviet bioweapons program is the time delay between the decision to expand the program and the actual start of renewed bioweapons work. When, in the early 1970s, Soviet authorities decided to expand the program, they faced three major obstacles: (1) the research and production infrastructure was insufficient; (2) the knowledge base had crumbled under the weight of the Stalin era; and (3) the scientific community was culturally isolated. Rebuilding the research and knowledge bases took several years of effort, pushing back the start of bioweapons work by about a decade.

The expansion of the program could not have been achieved without an influx of outside expertise and foreign equipment, all obtained covertly. To facilitate this process, the Council for Molecular Biology and Genetics was created within the Academy of Sciences. Its mission was to promote the development of modern biology within the overall scientific community, allow scientific exchange with the outside world, and serve as a cover for Biopreparat. Additionally, while its facilities were being built, Biopreparat sponsored research projects at open research institutes and universities, providing the agency with the funding, material, and equipment required to conduct its work, including imported equipment and reagents. Biopreparat also supported microbiology training of research fellows selected for future work in bioweapons facilities by placing them temporarily in civilian organizations, including anti-plague facilities.

As time passed, the symbiotic relationship between open institutes and MOD facilities turned into a vampirization process, wherein MOD and Biopreparat facilities seized research performed by civilian institutes on nonpathogenic strains and the methods they developed to support work with pathogenic strains. For example, as noted earlier, while Igor Domardskij headed the laboratory of Extrachromosomal Heredity of Microbes, he developed a method to introduce foreign genetic information into a vaccine strain of the plague bacteria. The method was then used at the MOD Kirov and St. Petersburg institutes to develop a virulent strain of plague that was antibiotic resistant. During that period, much of the work performed by open research institutes and anti-plague facilities led to several open publications and presentations at international conferences, which permitted Biopreparat to benefit from outside feedback and expertise. Finally, the cover of open research institutes and universities also permitted the acquisition of strains from overseas, supporting the creation of culture collections for genetic analysis.[74] In order to further leverage the growing expertise of civilian institutes, Biopreparat established some of its facilities in close proximity to existing universities and scientific centers.[75]

Although the establishment of Biopreparat's infrastructure is well documented, much of the literature fails to emphasize that the launch of bioweapons

work at these organizations was delayed by the need to train civilian personnel in techniques and methods used in bioweapons work. Indeed, the microbiology expertise acquired in civilian institutes was not directly applicable to bioweapons work. Additional training in specific microbiology methods and safety rules related to infectious material was necessary and was often provided by MOD scientists. For example, the Vector facility in Koltsovo was established in 1974 and hired most of its personnel from nearby Novosibirsk State University. During the first five years of the facility's existence, however, scientific personnel did not accomplish any bioweapons work. Instead, they spent this time working with innocuous bacteria and phages, learning the techniques that would be used to work with infectious material. Bioweapons work effectively started in the early 1980s, when the first laboratories with the appropriate equipment for working with infectious materials were built, and with the influx of military scientists sent to support civilian personnel.[76] A scientist who joined Vector in 1975 recalls:

> Then [in the early 1980s] a lot of things changed, people with knowledge on bio-safety appeared [at Vector], people who knew how to cultivate agents, people who knew how to deal with animals. . . . Many younger experimenters did not know how to deal with monkeys . . . and they really struggled to learn how to inject monkeys, how to deal with infectivity of animals, how to protect themselves, . . . so it was a steep learning curve.[77]

Delays in starting bioweapons work also occurred because much of the equipment and material needed to support modern science was unavailable in the Soviet Union. Reagents, enzymes, components of media for bacterial and viral cultivation, as well as devices and instruments such as autoclaves, instruments for lyophilisation, reactors, and chromatographs—all of these needed to be obtained from sources overseas. Although foreign assistance permitted jump-starting the program, Soviet authorities could not rely on foreign materials to sustain the program as it grew in size, for fear of subjecting the program to detection. They therefore launched appropriate sources of domestic production. For example, the Institute of Applied Enzymology in Vilnius, Lithuania, and dedicated departments at the Institute of Ultra-Pure Biological Preparations, the State Scientific Center of Applied Microbiology at Obolensk, and the State Research Center of Virology and Biotechnology (Vector) were created to produce scarce reagents and enzymes. Instruments and equipment were designed by various institutes in Moscow and produced at factories in Yoshkar Ola, Kirishi, Berdsk, and Penza.[78]

At production facilities, the delays caused by the lack of trained personnel and equipment were compounded by the need to test and integrate the production line. For example, after the accidental release of anthrax from the

Sverdlovsk facility in 1979, resulting in the decision of Soviet authorities to transfer the production of the anthrax weapon to the remote mobilization facility at Stepnogorsk, several years were needed to activate the facility. In addition to the scientific challenges associated with the adaptation of a production protocol originating from a different facility, Stepnogorsk personnel faced challenging engineering problems. Although most buildings and equipment had been established in the 1970s, few were in adequate working condition. Some of the equipment had not been installed properly or even been used. The buildings had been erected at different times, and no effort had been made to integrate them in a technologically coherent manner. As a result, the installation of each piece of equipment had to be checked and tested individually and as part of the system, while simultaneous engineering changes were being made to the infrastructure. Various tests of the whole production process had to be conducted with simulants, with an eye on safety, before any actual research and production work with infectious materials could start. These modifications required about two years of effort.[79]

DISRUPTIONS CAUSED BY THE SOVIET ECONOMIC SYSTEM

Another source of disruption in scientific work emerged from characteristics of the Soviet economic system. Interviews with former bioweapons scientists conducted in Russia, Kazakhstan, and the United States between 2006 and 2011 show that despite the high-level attention and priority status that the bioweapons complex enjoyed, it could not be shielded entirely from the shortages and bottlenecks that plagued the rest of the Soviet economy. The deficient supply system gave rise to power struggles and a decidedly negative incentive system while distracting bioweapons scientists from their scientific work, thereby decreasing their productivity and ultimately affecting the quality of their research and production outputs.

Contrary to common lore, the Soviet economy was a competitive system, but with a twist. Instead of taking place at the end of the production cycle—in the marketplace—competition concerned the allocation of resources and occurred at the beginning of the cycle. Competition was inevitable, due to the fact that the central planning system was highly inefficient and incapable of coordinating supply and demand.[80] In addition, the Soviet transportation and communication systems were designed to connect Moscow with the provinces, but very few connections existed between regions. In other words, everything had to pass through Moscow. As a result, the distribution of goods and materials was often slow and not adapted to regional needs. This gave birth to trends toward self-sufficiency and generated many conflicts that negatively affected the conduct of science.

As facility directors and laboratory heads could not count on a continuous flow of supplies, they had to plan ahead and order the supplies they

needed as much as two years in advance. However, since they could not plan for all contingencies that might have arisen during that time frame, they tended to order everything they could in bulk, hoping that they would receive some of the resources required to conduct their work. As a former Soviet scientist recalls:

> [Obtaining] even the simplest culture media to grow cells, to grow the first recombinants, clones, was a big problem. We sent telegrams to Moscow to get that particular media . . . . I still remember they could not help us. Biopreparat would say, "We do not distribute reagents you know; we provide directions on what to do, but the reagents are not our responsibility. You find the reagents you need, and you report your results to us." . . . [Eventually,] I think somebody in Moscow delivered the reagents just because of personal connections.[81]

As a result of these deficiencies, hoarding resources was a common feature of industry throughout the Soviet Union. An associated phenomenon, which also concerned bioweapons facilities, was the trend toward self-sufficiency. Because of the malfunctioning supply system, bio-facilities started producing what they would have otherwise purchased from existing suppliers. A scientist recalls an example of production started to offset the consequences of the deficient supply system:

> In many cases the organizations [facilities] took care of [producing] everything. [For instance, we did not go to] the supplier of radioactive chemicals. We did it ourselves. Then within my department there was a group, which specifically synthesized labeled nucleotides, another group purified solvents and so on.[82]

Consequently, instead of counting on guaranteed supplies for research, Soviet scientists were frequently held hostage to much more contingent ways of acquiring necessary materials and equipment for their work. In the 1970s through the mid-1980s, several articles published in Soviet scientific journals echoed the frustrations of life scientists who spent 30 to 60 percent of their time on administrative tasks related to procurement and planning. They also allocated a significant portion of their time to producing the reagents that could not be obtained from official supply channels.[83] If bioweapons scientists spent similar portions of their time on nonscientific activities, it is not surprising that their output was dramatically reduced. Attempts to reach self-sufficiency created oversized facilities, which compounded the supply system problem, as it implied higher resource requirements. The net result was a vicious cycle in which the cure was worse than the disease.

The competition for the allocation of resources also generated power struggles among agencies, facilities, and scientists, causing everyone to deploy

intricate networks of connections at the regional, national, and federal levels, to increase their chances of obtaining the resources they needed. A former manager at Obolensk recounts such behavior:

> The subordination of laboratories to various deputy directors—[Roman] Borovik, Tarumov, [Igor] Domaradskij—changed over time. For example, Igor Domaradskij would go to [Yuri] Kalinin [head of Biopreparat] and say: "How can this be? I am an experienced geneticist, a world renown scientist, and they [at Obolensk] give me only one laboratory [to supervise]?!" Then Kalinin would call the director [at Obolensk] and say: "Give him a couple of additional laboratories!"[84]

The struggle for power and the conflicts it generated further distracted personnel from their scientific work. They also disrupted the accumulation of knowledge, because individuals who acquired too much power and became potential competitors to their superiors or one of their colleagues were in danger of being replaced to thwart their rise. A former Obolensk scientist recounts an incident in which he was replaced after spending two years founding a pharmaceutical branch within a bioweapons facility:

> It was in the early 1990s when the decision was made to earn money [and be competitive]. We decided to produce recombinant proteins. . . . It took me about 2 years to set it up. . . . I thought . . . I would be getting some type of award. Instead of this, what happened? Ken Alibek [then Biopreparat's deputy director] sent me a deputy; when the deputy arrived, he said, "Please rely on me, I don't have anything against you. I want to be your subordinate, please rely on me." [This was Soviet double-talk, indicating] . . . that he had been sent to replace me.[85]

In some cases, individuals used the power of political organizations in their institution to solve personal conflicts or prevent someone's rise. For example, a scientist who was slated to become scientific director at Obolensk in the 1980s—a position immediately below that of deputy director—was prevented from getting this post and eventually fired because a colleague said that he read books about yoga and "stood on his head." In another case, party members at Obolensk seriously discussed whether they should allow a scientist to get married because his future wife did not have enough security clearances.[86]

These testimonies also illustrate the negative incentive system prevalent within the Soviet economy, which further disrupted scientific work. Since personal achievements were not necessarily recognized and rewarded, and political connections frequently mattered more than scientific performance, many scientists had little or no incentive to produce good work. Having a job in the Soviet system was a right; every individual was therefore "allocated" a job by central authorities generally in line with his or her education

or talents. Being unemployed was a rare occurrence and most often was due to political sanctions. Therefore, in order to obtain results from scientists, managers often had to design ways to motivate them, or to threaten them with sanctions.

Political interference with scientific work and disruptions caused by the faulty supply system directly affected the continuity and stability of work. In addition to distracting scientists from their work, these conflicts created an environment unfavorable to cooperation and collective work. As a result, scientists were less inclined to share information and help one another, thus constraining the creation of knowledge, as well as the spread of expertise and tacit knowledge to benefit the whole program. The centralization of decision making and the politicization of science created a disconnect between central authorities and implementing agencies, resulting in the identification of unattainable objectives. In this context, it is not surprising that bioweapons progress was slow.

Deleterious Scientific Behaviors and Problematic Integration

Finally, it is important to emphasize a less known consequence of the combined effects of political interference, the rigidity of Soviet central planning, the deficiencies of the Soviet economy, and the constraints of covertness. These four characteristics combined to promote the emergence of deleterious scientific behaviors that further complicated integration of scientific work at the end of the assembly line.

Because Soviet bench scientists had only limited opportunities to influence the often-unrealistic goals set by the top echelons of the Soviet hierarchy, they resorted to coping mechanisms that created a distorted picture of the work performed in the bioweapons program. These coping mechanisms included faking scientific results, defining research in view of achieving negative results, or defining tasks so narrowly that the procedures needed to accomplish an experiment became more important than the results.

Faking results was a common tactic that Soviet-era civilian and military facilities resorted to, driven by the severe consequences of not fulfilling the plan. Although there were several echelons of subordination embedded within the system, the superior echelons often turned a blind eye and sometimes even colluded with the subordinate levels, because the failure of entities under their control also affected their own performance. A former bioweapons scientist indicated that several committees were responsible for reviewing scientific results. But bench scientists knew that these committees would rarely question their results, because they did not want to report to higher authorities that their subordinates had failed to meet their goals under their watch.[87] He further adds:

> Biopreparat leaders . . . in many cases were well informed by the directors of the institutes on real achievements. They [Biopreparat leaders] were very selective on what to put in reports, and what kind of information to provide to the top [Communist Party leaders].[88]

Another tactic consisted in carrying out an experiment in view of failing it. For example, a scientist would identify successive interdependent stages to solve a problem defined by Moscow, knowing that the first stage could not be accomplished; thus, the rest of the experiment could not be completed. By doing so, the scientist could show that (1) he followed the plan, but (2) the task was complex and required more time and resources to solve the problem. In that way, a scientist could turn a situation in his favor that could have otherwise produced negative consequences—including sanctions or a decrease in allocated resources for failing to implement the plan.[89]

A variation of the previous tactic consisted of defining the tasks to be accomplished so narrowly that the actual results became secondary. By focusing on the procedural aspect of science—what task needs to be accomplished and how—scientists could then report that the tasks were conducted as prescribed by the plan, and therefore the plan was accomplished (even if the results were negative). The results of the tasks became secondary to the extent that they ceased to be the main measure of success. As a scientist described the phenomenon:

> You describe the experiment itself, you don't describe the result of the experiment . . . for example: you inject the animals with this, this and this. And that's your task. And if you injected [the animal], it does not matter what happened. So these tricks helped very much at different levels. . . . I've learned how to stage these artificial experiments . . . so that nobody accuses you that you did not do it.[90]

Another scientist reports the following tactics:

> Due to the rigidity of the requirements, there was always an attempt to give [Moscow] what they wanted . . . by presenting even minimal results that gave the impression that more significant results could be achieved. And this gave . . . the higher-ups the illusion that quality work was being done. As for me, I had no such illusions.[91]

The secrecy and compartmentalization that characterized the Soviet bioweapons complex enabled the doctoring of scientific results. Because scientific projects were fragmented, and different scientists, or teams of scientists, in different facilities did not normally talk to or know each other, it was easier to hide bad results or to fake positive results. The burden of identifying the faulty link or proving that a scientist lied about his results fell on those in charge of assembling these disparate inputs. Although fake

results might be intuitively detected, the only way to confirm their nature was to repeat the experiment; however, the scientific team at the end of the assembly line may not have had the time or the expertise to do so. The difficulty of integrating disparate pieces of any scientific project may have also been due to different laboratory practices used by the implementing teams, making the burden of proof even more complex. Because of the various levels of secrecy, a scientist may have also hidden behind the screen of privileged information to avoid providing details about how the work was conducted. A former scientist explains:

> Nobody knows about your results because it is all classified. So when nobody knows, then everybody realizes that you can report anything you want, until the very breaking point, when you need the product.[92]

Working under such circumstances, scientists at the end of the assembly line faced an arduous task. According to former scientists who performed this function, their only hope at receiving "honest" results, or becoming aware of a scientific report's distortions, was either to influence the selection of the contributing research teams or to place a trusted individual on the team.[93] This, of course, was not easily accomplished or accepted, because the new individual would be viewed as a potential threat to concerned scientists, thus worsening the effects of power struggles within facilities. New team members also faced the problem of rejection due to their intervention in core competencies of institutions already engaged on a specific technological path.

Clearly, the Soviet system did not present an optimal organization to ensure the creation, transfer, and institutionalization of knowledge. Four problems—luckily—contributed to poor results, particularly during the expansion phase of the program: fragmentation of scientific work, the assembly-line organizational model, deficiencies of the Soviet economic system, and measures to ensure covertness. Together they created a multitude of barriers to knowledge diffusion, while also impeding the collective interpretation of information and resolution of problems. In addition, the rigid management style led to a disconnect between the scientific personnel and the decision makers at the top, who consequently operated the program in a vacuum, without accounting for the realities of the supply system, scientific constraints, or the deleterious effect of political intrusion into scientific work. Accordingly, much of the resources invested in the program were wasted. Islands of innovation were created within the complex due to the actions of individual facility managers, but they remained isolated due to the rigidity of the overall system.

The Soviet case offers several important lessons that can inform future threat assessments. First, as this case illustrates clearly, access to financial, material, and human resources, however vast, is not a reliable indicator of a

program's achievements. Understanding how a program actually uses its available resources provides a more useful estimate of its potential achievements. Second, the Soviet case, like the American example, illustrates the power of disruptions in delaying a program. Whether caused by political intrusions, conflicts between individuals, or procurement problems, these disruptions all led to delays or even failures in achieving stated goals. The aftermath of Stalin's purges and the policy of Lysenkoism also strongly suggest that reviving a past program does not happen overnight, even with an extraordinary outpouring of human and financial resources. Re-creating a destroyed knowledge base and the relevant infrastructure is likely to require several years of sustained work, depending critically on the extent of knowledge decay.

Finally, the Soviet case illustrates oft-ignored consequences of covertness. Maintenance of a covert program not only dramatically raises the financial cost of an illicit program but also negatively affects scientific results. The need to ensure covertness led to the creation of a whole infrastructure and cadre of personnel not directly involved in bioweapons work, whose sole purpose was to serve as a screen to hide illicit activities. This not only inflated the financial burden of bioweapons work but also undoubtedly diverted funds from it. From the scientific point of view, the cost of covertness lies in its effect on knowledge management. To prevent detection, Soviet authorities had to disperse their facilities, reinforce security and compartmentalization, and do without system-wide integrative mechanisms—three factors that proved particularly damaging for knowledge production and program advancement. Covertness was also used to hide incompetence and failure. In the Soviet case, it favored the emergence of questionable work and reporting practices that cast doubts on the overall achievements of the bioweapons program. The practices of faking results and doing minimal work also raise doubts about the extent and quality of the work conducted. These reporting practices also imply that the recipients of the scientific reports, particularly those at the highest level of the Soviet hierarchy, at once possessed a distorted picture of the bioweapons program and little understanding of the work that was actually performed. Even scientific managers, such as those managing Biopreparat, had an obscured view of the actual program. Interestingly, the costs of covertness, both tangible and intangible, also had a profoundly adverse impact on other illicit programs, which we explore next.

CHAPTER 6

Small Bioweapons Programs and the Constraints of Covertness

Achieving covertness in a bioweapons program truly has the character of a double-edged sword. On the one hand, though it can shield an illicit program from outside scrutiny while the program seeks the materials needed to commence its objective, it can also be a powerful impediment to success, as the case of the Soviet bioweapons program demonstrates. Its increased financial burden and its effects on knowledge management can derail a program, even one with a long history of bioweapons development. We will see in this chapter that these same characteristics are also prominent in the most recently discovered state and terrorist covert bioweapons programs—those of Iraq, South Africa, and the terrorist group Aum Shinrikyo. In these three cases, however, the deleterious power of covertness was multiplied by two factors: their insufficient knowledge base at the outset, and the coercive character of their regimes. Whereas these three programs needed to establish a stable and continuous work environment to promote learning and create expertise, the requirements of covertness compelled them to select organizational and managerial models that restricted knowledge flow, created discontinuity in program developments, and prevented the successful passage from one stage of the bioweapons life cycle to the next. In addition, the coercive nature of these regimes along with disruptive exogenous variables—political intrusion (Iraq and Aum) and lack of oversight (South Africa)—fostered the emergence of corrupt scientific behaviors and resulted in a much diminished knowledge base at the end of the program. Unsurprisingly, due to this combination of all-around negative endogenous and exogenous variables, enhanced by covertness, all of these programs failed at all or key stages of weapons development, preventing them from producing a working weapon.

Different Circumstances, Same Model

In spite of their vastly different circumstances, Iraq's, South Africa's, and Aum Shinrikyo's programs shared a number of important characteristics. First, the three programs started with insufficient or nonexistent bioweapons expertise and a low absorptive capacity, leading to a steep learning curve. Second, the three programs selected organizational and managerial models similar to those of the Soviet Union, which optimized covertness at the expense of efficient use and transfer of knowledge. Structurally, they adopted a vertical model based on hierarchy and rules. Work was organized along fragmented and compartmentalized lines, with little to no coordination or integrative mechanisms. From the managerial point of view, the three programs selected an autocratic system, in which the top echelon of the hierarchy made decisions, frequently with no regard to scientific or technical feasibility. In addition, the three programs employed negative incentive systems. Individuals were not motivated to do good work, by either monetary compensation or positive recognition. Instead, they avoided retribution and punishment by falsifying results. Although this feature was also present in the Soviet case, in these three smaller programs the repercussions for failure were of a different nature: because they often consisted of threats to individuals' lives, the incentive to fake results was greatly enhanced, as was the concurrent waste of resources. Finally, the three programs selected personnel based on political loyalty rather than competence, thus creating a largely incompetent staff. As a result, these programs did not accumulate much knowledge over the years. Therefore, in spite of the fact that the three programs had access to outside expertise and material resources, and operated undisturbed for several years, they made very little, if any, progress at all.

Iraq's Bioweapons Program: The Development of a House of Cards

At first glance, the Iraqi bioweapons program appears to be a smaller version of the Soviet program. Both operated in a command economy based on a five-year plan, a highly centralized decision-making process, and seemingly limitless resources. The level of political intrusion in the Iraqi program was reminiscent of the Stalin era; so, too, was the violent and oppressive environment in which scientists had to operate. These features had the same deleterious effects on science, causing multiple disruptions, loss of knowledge, and bad science. A major distinction between the two programs, however, is that Iraq had a very limited knowledge base at the outset and no bioweapons expertise to rely on. As a result, after about twenty years of existence, the program was able to produce several thousand liters of crude liquid agents, such as anthrax and botulinum toxin, but failed at drying these agents and developing efficient dissemination mechanisms, thus making them highly ineffective as weapons.

PROGRAM OVERVIEW

Launched in 1974 and terminated in 1996, Iraq's bioweapons program met its demise as mandated by a United Nations resolution that effectively led to the destruction of its infrastructure in the aftermath of Iraq's failed attempt to invade Kuwait in 1990. The Iraqi program included about thirty facilities, organized in a way very similar to the Soviet bioweapons complex. A core of half a dozen facilities were directly involved in research, development, and production activities, while a wider circle of institutions contributed to bioweapons work in varying degrees and ways. Some universities and research centers, for example, were used as a source of trained personnel, while other educational institutions and companies acted as a cover to procure equipment and biological agents. Still another group of institutions engaged in the design and construction of bioweapons facilities, as well as the manufacturing of equipment. So as to ensure covertness and facilitate procurement of agents and laboratory equipment from overseas, many of these facilities were ostensibly civilian and placed under the authority of a variety of agencies, including the Ministries of Health, Agriculture, Defense, and Higher Education and Scientific Research, as well as Iraq's Intelligence Service.[1]

Administratively, the program came under the authority of the Military Industrial Commission (MIC), which Hussein Kamal, Saddam Hussein's son-in-law, headed. Interestingly, the program did not seem to have a fixed annual budget, as Kamal disbursed the funds as needed. His budget decisions were not subject to review, which allowed a quick allocation of funds but also provided greater opportunities for wastefulness. In addition, many of the services and activities under the program were funded out of the budgets of other agencies, which loaned or were asked to provide equipment, facilities, or personnel without compensation. For several years, the bioweapons program came under the Ministry of Industry and Military Industrialization (MIMI), also headed by Kamal, who could mobilize any part of Iraq's industry to support weapons work, thus further blurring the contours of the program and its funding. Accordingly, the total budget of the program is unknown. Estimates, however, place it in the tens of millions of dollars, with $80 million invested between 1985 and 1990 alone.[2]

Although the program's infrastructure suggests a sizable endeavor, by the time the program ended in 1996, the results were less than meager. Iraqi scientists studied several classical biological agents, such as anthrax and botulinum toxin, and researched the causative agent of gas gangrene, mycotoxins—particularly aflatoxin—as well as bacterial simulants, ricin toxin, and wheat smut.[3] Although they produced several thousand liters of these agents in liquid form, the solutions were crude, and their toxicity decreased within six to eight months, which implied that the produced batches could not be stored for long periods. Moreover, Iraqi scientists were unable to dry these

agents, in spite of having access to drying equipment. They also researched several viruses, but these efforts failed,[4] and their work in the critically important area of aerosolization also failed. They did load liquid forms of anthrax, botulinum toxin, and aflatoxin in an arsenal composed of one hundred bombs and approximately twenty-five Al Hussein ballistic missile warheads. However, these dissemination mechanisms were inefficient: release of the agents was to occur upon impact, which would have destroyed most of the agents.[5]

INSUFFICIENT KNOWLEDGE BASE AND PROGRAMMATIC DISCONTINUITIES

One of the key sources of failure in the Iraqi program was its insufficient knowledge base. Iraq not only lacked expertise in key areas of the bioweapons life cycle but also was unable to accumulate knowledge over time due to the discontinuity of its program.

Although it lasted about twenty years, the Iraqi bioweapons program is more accurately described as a succession of three separate programs, each conducted independently from the other and with little or no transfer of knowledge, thus limiting knowledge accumulation and learning. When the program was originally launched in 1974 at the Al Hasan Institute, officially under the authority of the Ministry of Higher Education, work centered on investigating anthrax, botulism, and influenza as potential bioweapons. This program quickly faltered and four years later was terminated. Iraqi authorities maintain that the main reason for termination was that the program was subject to scientific and financial fraud. It is not clear, however, whether or not fraud actually occurred, or if this was the excuse used by bureaucrats to hide failure at higher levels. Evidence collected by UN inspectors in Iraq after the 1991 war suggests that this initial program was staffed with competent scientists trained in academic institutions who nonetheless accomplished little due in part to the program's apparent lack of direction from higher authorities. Scientists were left to identify what type of work should be pursued but did not seem to know how to achieve these goals. In addition, there is no evidence that they conducted a systematic search of the literature to identify suitable bioweapons agents. Consequently, much of their work was devoted instead to academic research, which might have been construed as fraud by higher authorities. Nevertheless, several scientists were prosecuted, while the rest of the staff and the equipment were spread across several scientific establishments, effectively destroying whatever collective knowledge might have been developed during the previous four years.[6]

Soon after the initial effort folded, a second program commenced in 1979 at Salman Pak, a facility controlled by Iraq's intelligence services. Although it is believed that a small number of the scientists that comprised the original effort were moved to Salman Pak, Iraqi authorities stated that there was no

continuity between early efforts and new work at Salman Pak. It is probably true, since research projects at Salman Pak evolved around a plant disease—wheat smut—and possibly assassination weapons, not human diseases, as in the original effort. The work conducted under this second program is believed to have remained at a low scale, achieving little, possibly because of the lack of expertise. Indeed, the earlier attempt at developing bioweapons demonstrated to Iraqi authorities that existing expertise was insufficient. As a result, several scientists were sent abroad for further education in various areas of microbiology.[7]

In 1983, Iraq launched a parallel program within the Al Muthanna chemical weapons facility, which reported to the Ministry of Defense. Dr. Rihab Taha, who had just returned from Britain, where she completed her PhD in microbiology, headed this new effort. Eight other scientists soon joined her. According to data gathered by UN inspectors, Taha adopted a methodological approach consisting of first conducting a systematic search of the literature about past bioweapons work. Concluding that anthrax and botulism would be the best candidates for bioweapons, she and her team conducted basic growth, toxicity, and pathogenicity research on those agents, as well as lab-scale production for about three years. After writing a progress report in 1986 indicating that further developments would require more funding and the establishment of testing and production facilities, the group was moved out of the Al Muthanna facility in 1987 and joined with the Salman Pak group. The whole bioweapons program was then placed under the MIC, headed by Hussein Kamal, and given the mission to develop a biological weapon within five years.[8]

Although the bioweapons program grew to involve a relatively large number of facilities, it relied on a small number of employees. UN inspectors estimated that at its peak in 1990, about one hundred people were directly involved in bioweapons work. Among them, only about twenty-five were key personnel involved in research, production, field testing, and weaponization. The remaining seventy-five were support and administrative personnel. Another contingent of individuals employed at the Al Muthanna chemical weapons facility also contributed to the bioweapons program by designing and filling biomunitions and assisting in bioweapons testing. Their number is not known.[9] Among the twenty-five bioweapons specialists, only a handful had PhDs. The others had bachelor's degrees in science or engineering. Later on, when micotoxin research began, three more PhDs were hired, and a few months before the 1991 Gulf War, another PhD was recruited to start research on viruses.[10]

Even the key scientists, however, did not have expertise directly applicable to work with the microorganisms selected for the program. For example, although the program's head, Rihab Taha, received a PhD in microbiology at Britain's University of East Anglia, her expertise lay in plant pathogens, particularly Tobacco mosaic virus. Yet Iraq's bioweapons program centered

on human diseases caused by bacteria and toxins.[11] Her scientific abilities also seemed to have been insufficient for her job. Her former professors at the University of East Anglia remember her as a "less-than-brilliant student."[12] Several UN inspectors doubted that she was the actual head of the program, because her expertise seemed subpar. Taha herself once told UN inspectors that she wanted to become a medical doctor, but as her grades were not high enough, she instead became a microbiologist.[13] However, Taha was a loyal Ba'ath Party member, and probably owed her position to her political connections.

Another key bioweapons program scientist, Huda Ammash, was the dean of the College of Science at the University of Baghdad, and received her PhD in microbiology from the University of Missouri. Her field of expertise—cancer research—also does not seem to have been a good fit for work on anthrax and botulinum. Nonetheless, some UN inspectors believed that she played a greater role than Taha in managing the program. This might have been a reasonable assumption, considering that she was part of Saddam's inner circle and a member of the Ba'ath Party, suggesting that her selection, too, may have had more to do with politics than appropriate expertise.[14]

Only a handful of individuals had expertise applicable to their bioweapons work. For example, two fungus experts studied aflatoxin—a fungus that causes cancer—as a bioweapon.[15] However, aflatoxin is not a good candidate for bioweapons because of its slow effects: cancer may occur several years after exposure. It is possible that in their case the available expertise influenced the choice of agent. Another scientist, Dr. Hazem Ali, was a virologist and started the virus program. However, he was recruited about six months before the Gulf War started, and the work was interrupted before he could achieve anything.[16]

The only individual whose experience was directly relevant and useful for the program was Dr. Nassir Hindawi. Officially, Hindawi was a consultant to the bioweapons program, but he may well have been the mastermind behind it. A U.S.-trained scientist, Hindawi was a respected microbiologist and fermentation expert, who reportedly prompted Saddam to revive the bioweapons program during the war with Iran (1980–1988). Hindawi was also a former professor and mentor of Taha and Ammash, whom he recruited for the program. Having practical knowledge in fermentation, Hindawi was instrumental in helping the program move from laboratory-scale to larger-quantity production. Before he joined the program in 1987, no one had any fermentation expertise, and the pilot-scale 150-liter fermentor previously purchased had remained in its crate for lack of knowledge about how to use it.[17] Hindawi is believed to have served as a master trainer for the program, not only by providing scientific advice to Taha and Ammash but also by directly training about fifty technicians in scale-up procedures. These technicians were then placed in the program's production facilities.[18] Hindawi's

direct involvement in the program, however, lasted less than two years, limiting his ability to foster progress over the long term.[19]

Thus, the Iraqi bioweapons staff not only lacked expertise directly applicable to bioweapons work but also did not have the appropriate range of expertise and knowledge required to conduct the various stages of a bioweapon's life cycle. Under such conditions, they faced a steep learning curve, which, to be overcome, required organizational mechanisms of knowledge transfer and a stable and continuous work environment. Yet the Iraqi leadership's autocratic management style, coupled with the general environment of fear, greatly hindered the learning process.

COMPARTMENTALIZATION, AUTOCRATIC MANAGEMENT, AND LACK OF DIRECTION

Although details about work organization at the facility level are limited, existing information suggests that scientific work was compartmentalized and fragmented. For example, scientific work within the bioweapons program was organized around small, compartmented groups, in which a senior researcher or a technician with experience working on a particular organism managed and trained less experienced scientists. According to the Iraq Survey Group, production was organized along the same lines with "small cadres of skilled personnel to lead clusters of less skilled personnel in the production process."[20] Because of their compartmentalization, however, it is unlikely that these small groups were able to easily learn from each other and overcome their lack of expertise.

In addition, there seemed to have been no integration and coordination mechanism at the program level. Structurally, work on different agents and different stages of the bioweapons life cycle took place at different facilities. For example, the work on ricin occurred at Salman Pak, and program head Taha did not know of its existence. Work on aerosolization was also undertaken independently from scientists who conducted research on the agents. Staff at the Al Muthanna chemical weapons plant worked on developing missile warheads, but they were largely unaware that the warheads they were building were meant to deliver bioweapons.[21]

Hindawi was the most technically advanced member of the program and possibly the only individual who had a history of mentor-apprentice relationships with various members of the program—Taha, Ammash, and production plant technicians. From this point of view, Hindawi probably served as an informal integrator. However, because his direct involvement in the program was so short-lived, it is unlikely that his function was taken over by someone else, due to the absence of similar expertise within the program.

From the managerial point of view, the program suffered from both a violent autocratic management and a lack of strategic direction. Although Kamal was responsible for the bioweapons program's overall management

and decision making, he had no scientific expertise, and he gave very little direction to the program: there was no long-term planning or even strategic or technical oversight of the work conducted at the various facilities. According to Rod Barton—a member of the Iraq Survey Group—Kamal visited bioweapons facilities only a couple of times, and was impressed by the fermentors and test tubes. As long as the program seemed to be making progress, he was satisfied.[22]

In spite of this apparent laissez-faire attitude, scientists were under substantial pressure. Failure could lead to imprisonment or death, whereas success was generously rewarded. This promoted a culture of embellishment of scientific results. For example, Rod Barton indicated that bioweapons tests on animals were never reported as failures: if fewer animals than expected died, the reports indicated partial success. Some tests were run several times with slight changes, including the placement of animals closer to the bomb to ensure a greater number of casualties. That way, Taha could report increased success and reap the rewards. Annual reports typically showed only positive results. Kamal's direct subordinates, Generals Murthada and Al Sa'adi, did not seem to have great interest in the bioweapons program or in reviewing its results. Their role seemed to be limited to ensuring that the program had the required resources, and instructing the scientific managers on the importance of achieving success. The pressure imposed by the hierarchy trickled down to the lower levels and translated in mistreatment of scientists by program head Taha, who regularly verbally abused subordinates.[23]

This work environment was not ideal for learning, detecting and solving problems, or making progress. The lack of direction also contributed to the program's failure. Scientific decisions after Hindawi's departure were mostly left to Taha, who, due to her lack of expertise and pressure from above, viewed modest progress as a substantial achievement. As a result, the program evolved haphazardly, with no clear objective apart from satisfying the whims of Hussein Kamal and Saddam Hussein.

POLITICAL INTRUSION

Although Saddam Hussein and Hussein Kamal did not directly intervene in the day-to-day management of the bioweapons program, as they did with the nuclear program, the general environment of fear and pressure they created, and their interventions in personnel selections, depleted the ranks of competent scientists available for the bioweapons program and directly affected scientific progress.

Saddam Hussein—like Stalin in the Soviet system—was interested in science as a means to promote development and military power. He often requested updates on specific defense projects or facilities from Hussein Kamal. Although nothing similar to Lysenkoism emerged in Iraq, Saddam would

often handpick and promote scientists who proposed projects that spoke to his aspirations. Because scientists with political connections were able to submit their proposals directly to Saddam, without prior review by a panel of experts, military programs were riddled with pet projects that had little scientific grounding. In one case, a pharmacist sponsored by Saddam claimed that he had developed an ointment capable of treating gangrene. When physicians refused to use the miracle cure on their patients without knowing what ingredients composed it, the pharmacist showed up at hospitals with a letter from Saddam and accompanied by Saddam's bodyguards. The physicians were compelled to use the ointment on their patients, which was ineffective. Unless someone knowledgeable and trustworthy was able to intervene, projects would continue regardless of their scientific merit, often resulting in costly failures.[24]

In general, however, Saddam did not suffer contradictions and demanded immediate results. Subordinates who dared to raise dissent, even at the urging of Saddam—or otherwise displeased the supreme commander—would disappear or be summarily executed. Interestingly, Saddam's violence vis-à-vis his subordinates was also his weakness and a source of his many delusions. Senior Iraqi officials indicated that even if they knew that Saddam's orders could not be implemented, they nonetheless enthusiastically endorsed his projects and provided fabricated reports and results when Saddam requested updates. Saddam rarely demanded demonstrations, allowing the culture of false reporting, reminiscent of the Soviet system, to spread across all types of defense projects in Iraq. The impact affected military preparedness, making Saddam completely unaware of the actual readiness of Iraqi military forces.[25]

Kamal himself manipulated Saddam into believing that the WMD programs were more advanced than they actually were. Surely, his family ties with Saddam gave him broad authority and independence, but he was also acutely aware of the dangers of disappointing his father-in-law. Thus, he often exaggerated achievements to gain more influence and power, and also to convince Saddam that he was a more worthy successor than even Saddam's oldest son, Uday.[26] By the time Kamal defected to Jordan in 1995, the MIC was in shambles through mismanagement and inefficiency.[27]

In the bioweapons field, political interference was a direct contributor to program failure. First, political intrusion in science prevented the development of a cadre of professionals due to the practice of selecting personnel based on loyalty rather than on competence. At the outset of the bioweapons program in the 1970s, Iraq placed emphasis on creating a solid knowledge base, relying on the best scientists selected from top universities and sent overseas for further education. The selection criteria changed in the mid-1980s under Kamal, who favored scientists loyal to the regime. Kamal institutionalized the system by means of a program called Al Mumtazin (the

Distinguished), which selected candidates for postgraduate education based on their political affiliation.[28] Corruption and cheating also ran rampant throughout the educational system: Ba'ath Party members who wanted a university degree were given the answers to final exams in advance and at times took their exams in the dean's office, with professors present to provide the answers when needed. In the 1980s, Iraq's leadership fired more than forty physicians and professors who had received their education in Europe and who formed the backbone of Iraqi medical research. Their positions were given to young doctors with connections to the Ba'ath Party.[29] As a result, Saddam and his son-in-law, very much like Stalin and Beria, created a whole generation of largely incompetent scientists and unqualified civil servants with little to no technical expertise.

Second, the environment of fear and violence led scientists to make technical decisions they knew would fail. For example, with the expectation of a war after Iraq invaded Kuwait in 1990, Saddam and Kamal pressured program managers to build up production and accelerate weaponization. As a result, program managers abandoned the dissemination mechanisms they were working on in favor of less-than-optimal alternatives. They quickly modified chemical R-400 aerial bomb munitions and Al Hussein missile warheads to meet the leadership's requirements. However, the selection of means of delivery was not based on their efficiency as dissemination mechanisms for bio-agents but on their being easier and safer for the Air Force to use. The scientists and military leaders understood that most of the agents would be destroyed upon impact; they hoped, however, that enough material would survive to be detected and thereby create panic among foreign troops.[30]

Ultimately, the failure of the Iraqi program was primarily due to the leadership's inability to realize how limited the country's knowledge base truly was. Instead of making the organizational and managerial accommodations to ensure knowledge acquisition, the leadership dominated scientific decision making and, in the process, not only corrupted science but also created a whole cadre of largely incompetent scientists. This only further reduced the knowledge base and the scientific staff's absorptive capacity. In addition, the demands of covertness and the program's coercive character favored the program's mismanagement and created incentives to hide its failures.

South Africa's Bioweapons Program

Like its Iraqi counterpart, the South African program, known as Project Coast, had access to ample funding and materials and, at the start, a cadre of personnel trained in the life sciences. Unlike the Iraqi program, however, Project

Coast did not suffer from the political intrusion that characterized Iraq's bioweapons endeavors. Instead, Project Coast was virtually an independent entity run by its head scientist, Wouter Basson. South African political and military authorities gave Basson carte blanche in deciding what type of work would be conducted and what kinds of agents would be studied. With the full backing of political and military authorities, access to expertise inside and outside South Africa, scientific freedom, and sufficient funding, the program should have been successful. Yet it was a complete failure. The reasons lie in Basson's organizational and managerial choices, which failed to exploit the extant knowledge base, let alone build on it. The heavy compartmentalization that prevailed within the program was accompanied by a coercive and autocratic management style, which not only created an unfavorable work environment but also allowed Basson to hide failures from the military and political establishments. Finally, low political intrusion translated into a complete absence of oversight and no mechanisms to hold Basson accountable, allowing him to divert much of the program's resources for personal gain.

PROGRAM OVERVIEW

When Project Coast was officially established in 1981, the program had no prior bioweapons expertise to rely on. Wouter Basson—a physician by training—traveled around the world, attending conferences and visiting biological research facilities to gather intelligence about other bioweapons programs that could support South Africa's bioweapons developments. It is unclear how much scientific information he was able to gather, but Basson's travels seem to have influenced the organizational structure of Project Coast. Upon returning from his trip, Basson convinced his Ministry of Defense superiors to create a bioweapons program based on private companies—a structure, he stated, the American and Soviet programs had used to ensure the secrecy of their activities. Although this information was erroneous, Basson was given the green light to establish several front companies and launch the biological weapons program.

Project Coast, which combined both chemical and biological weapons activities, was seemingly a small enterprise relying on a modest group of facilities. However, much like the Iraqi and Soviet models, it comprised several concentric circles of institutions with a more or less direct relationship to bioweapons work. The core consisted of three main facilities: Roodeplaat Research Laboratories (RRL), Delta G Scientific, and Infladel. Among these, only RRL was involved in bioweapons work. Ostensibly, RRL was established in 1982 to conduct research in pharmacology, as well as agricultural, veterinary, and medical sciences. To ensure the credibility of its cover, about 15 percent of its activities were constituted as private proj-

ects conducted by scientists who published papers in these fields. Although RRL and Delta G Scientific cooperated on some projects, the latter organization was primarily involved in chemical weapons work, while Infladel was the administrative arm of the program, used secretly to disburse funds from the Ministry of Defense to RRL and Delta G Scientific. Project Coast's core facilities employed a total workforce of about two hundred, with about seventy employed at RRL.[31] Project Coast also included several second-tier institutions, which knowingly or unknowingly contributed to the program. Several satellite companies were set up to provide various services and conduct minor production, such as the design of assassination weapons, while local universities provided personnel or conducted work for the program.

Financially, the program was well endowed. Due to the labyrinth of companies created by Basson and the secrecy surrounding the program, total budget estimates vary from approximately $30 million to as much as $100 million.[32] As RRL's former director, Daan Goosen, indicated, "Financially we had quite a bit of leeway in those days if you were involved in the military effort and it wasn't really strictly controlled how much money was spent."[33]

During its fourteen years of operation, Project Coast yielded meager results. The program did not produce any significant scientific breakthroughs, and no large-scale production was ever conducted. The program also seems to have been stuck in the exploratory phase. Over its life span (1981–1995),[34] the program reportedly investigated a number of agents, including anthrax, *E. coli*, *Salmonella*, botulism, cholera, ricin, the flesh-eating bacteria necrotizing fasciitis, and possibly hepatitis A and HIV. Several sources indicate that RRL scientists might have also researched Ebola, Marburg, and Rift Valley viruses, having obtained strains of these diseases from the American Centers for Disease Control (CDC) in Atlanta, Georgia. Yet most of RRL's work focused on the development and testing of small quantities of poisons, not on the production and weaponization of bacteria and viruses.[35]

Among its assassination devices, Project Coast's scientists concocted chocolate and cigarettes containing anthrax and botulinum; *Salmonella* hidden in whiskey and sugar; deodorant infected with paratyphoid; beer bottles with botulinum; anthrax spores spread on envelope flaps; as well as screwdrivers with syringe mechanisms, umbrellas, and walking sticks designed to inject poisonous substances.[36] There is no evidence that any of these assassination agents actually worked, but Project Coast provided several of these instruments to South Africa's Death Squads, which executed enemies of the apartheid regime. A common practice of the Death Squads was to kidnap political activists and load them onto a plane, where they were injected with the substances developed by RRL. The targeted individuals were then thrown out of the plane over the ocean—dead or alive.

Members of RRL were at times involved in these execution missions and tested the material they developed. RRL appears also to have furnished cholera that was used to infect drinking water in refugee camps in Namibia. RRL scientists also experimented with veterinary antibiotics and reportedly found that the administration of large doses had a lethal effect on human heart function and were not traceable postmortem.[37]

Although it is generally believed that the program was not designed to produce weapons for military use, there is evidence that South African authorities intended to produce weapons based on bacteria and viruses, as in other larger bioweapons programs. For example, RRL documents released by the Truth and Reconciliation Commission indicate that the program's leadership established an objective of developing antibiotic-resistant anthrax in dried form as well as botulinum toxin–based weapons. There is also evidence that South African authorities intended to scale up and weaponize bacterial and viral agents. The program's managers made plans in the mid-1980s to build a larger research and production facility equipped with a BSL-4 laboratory, 300-liter fermentors, freeze-drying equipment, and a storage facility. RRL had already spent about $100,000 in drawing up plans for this new facility, but in the late 1980s—two years after launching the project—it decided to scrap the project due to a funding shortage.[38] Whether it would have been successful in this endeavor, however, is doubtful, considering that even with its more limited objective, the program was heavily constrained by its available knowledge base, its covertness, as well as organizational and managerial features that prevented the efficient use and creation of knowledge.

INSUFFICIENT AND CORRUPTED KNOWLEDGE BASE

Like the Iraqi program, Project Coast went through several stages leading to an increasingly diminished knowledge base. According to former Project Coast scientists, the program went through two major phases. During the first phase—from RRL's inception in 1982 to 1987—Basson hired individuals with scientific credentials and expertise potentially applicable to bioweapons to conduct and manage scientific work. During his testimony before the Truth and Reconciliation Commission,[39] which investigated the bioweapons program's activities in the late 1990s, Basson claimed:

> There is not a university in South Africa that was not involved in some way or another, it was widely distributed, as far as possible we supported all the universities and we also paid them for work they had done. As far as private companies is [*sic*] concerned there were several of them; it could be a state, it could be semi-state companies, some of the people in agricultural research. I really cannot remember but there was a diversity of facilities we made use of.[40]

Although Basson often made outlandish public statements, the relationship between Project Coast and local universities seems to have existed at least during the first phase of the program. Although current evidence suggests that none of the staff recruited from local universities had prior bioweapons experience, they nonetheless had expertise in fields relevant to biological weapons development, including microbiology, toxicology, pathology, veterinary science, and medical science.[41] For example, RRL's first director, Daan Goosen, was a veterinarian with a degree in clinical pathology, toxicology, and pharmacology, and a member of the veterinary studies faculty at Pretoria University.[42] In addition, many of the program's scientists maintained positions at or connections with local universities, and given the ostensibly civilian nature of RRL, they could also draw on external expertise in South Africa and overseas.[43] Former director Goosen also indicated that the military provided servicemen with skills in microbiology, genetics, and veterinary science to work in the program.[44]

According to former Project Coast scientists, the program evolved steadily under Goosen's tenure, following a regular developmental path in which scientists acquired and researched a variety of bioweapons agents, including classical ones such as anthrax and botulinum toxin. Plans were also drawn up during this first stage to expand activities, with a view toward launching large-scale production.[45]

Starting in 1988, however, this steady progress was perturbed by a progressive change in personnel. During this second phase of the program (1988–1995), Basson turned to recruiting trusted friends from the Special Forces with little expertise to offer. For example, when Goosen fell into disgrace, Basson replaced him in 1988 with Wynand Swanepoel, a Special Forces dentist.[46] Swanepoel himself indicated that he had no knowledge of what was being done in the laboratories, and scientists testified that he had no interest in their work.[47] Under Swanepoel, the program became unfocused, veering away from the traditional bioweapons development path. Scientists working at RRL later reported that they received no scientific direction from the new director and instead started doing research fitting their personal interests. They ensured approval for this research by claiming that the work might have military applications. Yet when scientists achieved results with actual military potential, neither Swanepoel nor Basson made any attempt to extend such research to actual bioweapons development.[48] It is possible that the looming end of the apartheid regime had an impact on the program, as South African authorities started to make plans in the late 1980s to wind down weapons activities. In the bioweapons program, however, potential regime change did not seem to have been the main impetus for the program's faltering: plans were still being made to build a large-scale production facility in the late 1980s. A more plausible explanation is that Basson used these circumstances to increase his control over the program to better divert its resources for personal gain.

COMPARTMENTALIZATION AND COERCION

Although Basson did not spend much time in the laboratories, his autocratic management style, and the strict secrecy that prevailed within the program, had a direct influence on how science was accomplished under the program. Conducted in contravention of the Biological Weapons Convention, South Africa's program was highly compartmentalized and coercive, which further prevented the use of extant knowledge. Knowledge of Project Coast activities was limited to Basson and a small circle of managers selected by him from a network of trusted friends, less for their expertise than for their loyalty to him. Private companies involved in the program did not know what other Project Coast companies did. Scientists did not know how the substances they developed were to be used, and they were subject to stringent security measures. Similar to the Soviet model, scientists were prohibited from discussing their work with colleagues involved in other projects, and access to laboratories was also strictly limited. Orders to start new projects were given orally, and paperwork was kept to a minimum to reduce the potential for detection.[49]

In addition to strict security measures, scientists were subject to intimidation and threats if they raised concerns about their work or discussed the possibility of leaving the program. Some scientists were even subjected to electronic surveillance in their homes and thus feared for their lives. Those who, in the eyes of Basson, appeared to pose a security threat were killed or otherwise incapacitated.[50] Such measures created an oppressive and suspicious work environment, which not only limited scientists' willingness to cooperate and exchange information but also prevented access and transfer of information throughout the program. According to RRL's first director, Daan Goosen, most scientists carefully avoided asking questions about the use of the substances they were producing. Basson saw this as an effective means of controlling information. However, Goosen recognized that the staff's lack of knowledge imposed a limiting effect on their ability to develop effective agents because they were not given sufficient information, such as the assassination target's weight or the climate in which the agent was to be used, thus—thankfully—compromising the weapon's efficacy.[51]

LACK OF OVERSIGHT

Basson's absolute control over information was much reinforced by the absence of oversight from political and military authorities, in part caused by the existence of competitive reporting channels. Officially, Project Coast was under the purview of the surgeon general and the Coordinating Management Committee of the Ministry of Defense; Basson was in charge of daily management and reported on the program's developments to the surgeon general on a monthly basis. In reality, however, Basson had informal

reporting channels, which bypassed his direct supervisors and reached directly to the minister of defense and possibly the president. As a result, his official supervisors received only scant reports about the program's work, and the role of military overseers was mostly limited to signing off on budget requests.[52] Due to his ability to reach high into the political hierarchy, Basson was able to silence dissent within the Ministry of Defense by engineering the removal of ministry employees who raised concerns about the program's direction or use of funds. Consequently, it became routine within the ministry to avoid questioning Basson's reports or decisions.[53]

The multiple reporting channels combined with the lack of scientific expertise within the hierarchy had the effect of giving Basson a free hand in program decision making, and allowed him to control outside knowledge of the program. For example, many of the front companies Basson established to serve as a cover for the program were created without knowledge of the hierarchy. During hearings investigating the handling of Project Coast finances, conducted by South Africa's Office of Serious Economic Offenses in the late 1990s, the minister of defense himself did not seem to know about these companies and had to ask Basson what their activities were.[54] Similarly, the surgeon general admitted that he had little knowledge of the scientific work conducted under Project Coast.[55]

With limited technical or financial oversight from his hierarchy, Basson was able to misappropriate large sums of money through private companies managed or nominally owned by individuals loyal to him. To make it difficult to trace their movement and activities, the names of these companies and their shareholders were purposefully changed regularly.[56] And to divert funds from the program for personal use, Basson opened several bank accounts in South Africa and overseas under his name or those of his close associates or family members.

Basson was known for his lavish lifestyle, and Project Coast employees, who received generous salaries, occasionally accompanied Basson in his numerous travels overseas on the private jet he purchased with Project Coast funding.[57] Many of these expenditures were made with the explicit or tacit blessing of his superiors, who rationalized such nonscientific purchases by the need to maintain the cover of a private and successful pharmaceutical research enterprise run by Basson. Even scientifically justified purchases were used to defraud the government. For example, in 1988, Basson reportedly purchased a peptide synthesizer for more than $2 million, to support a line of research aimed at developing a weapon that would alter brain functions of black people. One Project Coast scientist later reported that the synthesizer was never purchased; in all likelihood, Basson diverted the funds for his personal use.[58] Although Infladel—the administrative arm of Project Coast—was responsible for managing RRL's finances, it did not conduct physical audits of purchased equipment, thus allowing such diversions to occur.

The South African example is a powerful illustration of the influence managers exert on scientific achievements and how covertness can be used to hide failure. In spite of seemingly ideal conditions at the start of the program, the absence of oversight and heavy compartmentalization prevented the use of the knowledge available at the start and allowed Basson to squander the program's resources. Given these conditions, it is unlikely that the South African program would have been able to produce a working bioweapon capable of truly mass effects. Complex research requires the creation of an environment conducive to cooperation and information exchange, ideals that Basson clearly did not embrace.

Aum Shinrikyo

Although Aum's program did not benefit from the backing of a government to protect it against outside scrutiny, it nonetheless benefited from exceptional circumstances that permitted the group to pursue unfettered bioweapons work for about six years without raising suspicions. The Japanese cult Aum Shinrikyo appeared on the world stage in 1995, after the group, founded and led by Shoko Asahara in 1984, launched a sarin gas attack in the Tokyo metro, killing thirteen and injuring thousands. Soon after the cult leader's arrest, it became known that Aum had also engaged in bioweapons developments, attempting to produce and disseminate the causative agents of anthrax and botulism. Due to its religious organizational status, the cult was shielded by law from intrusive police interventions and domestic intelligence operations. Despite numerous incidents and releases of biological and chemical materials that led to complaints by local residents about foul odors, the group's activities were not fully investigated or understood until after the sarin attack of 1995.[59] The group's legal status also enabled it to benefit from tax exemptions, which permitted its leaders to invest large amounts of money derived from the group's business and illicit activities into bioweapons work. Aum reportedly spent about $10 million in its biological weapons program to procure equipment, build facilities, and acquire scientific documentation and bio-agents.[60] In spite of these seemingly ideal conditions, however, the group's attempt to develop biological weapons failed. Much of the literature underscores two sources of failure: the inability to overcome technical difficulties associated with the development of bioweapons, and the lack of access to virulent biological strains.[61]

A closer analysis of the group's makeup and activities, however, reveals other sources of failure. From the outset, the group had an enormous handicap to overcome: its lack of bioweapons expertise and its consequent low absorptive capacity. Yet the program's organizational and managerial shortcomings served to inhibit learning and knowledge accumulation. Finally, the group's practice of isolating and committing violence vis-à-vis its own

members further inhibited communication and information sharing, thus preventing the early identification of problems or sources of failure.

LACK OF BIOWEAPONS EXPERTISE

In its recruiting efforts, Aum was known for targeting educated and well-off individuals who could shore up the group's coffers and support its weapons activities. Reportedly, the group included 107 members with scientific backgrounds, including those in such areas as medical science, biology, pharmacology, and veterinary and agricultural studies. Among them, eight were part of the group's inner circle. The head of the biological weapons program, Seiichi Endo, had studied molecular biology and genetic engineering while pursuing a veterinary undergraduate degree, and later pursued a graduate degree at the Institute for Virus Research at Kyoto University, with an emphasis on cancer studies. Another inner-sanctum member who was also part of the bioweapons team, Tomomasa Nakagawa, was a physician who had quit his job after one year of practice to join the group. The total number of cult members involved in Aum's chemical and biological programs is estimated to have been between thirty and forty, although it is not clear how many of them had a biology-related background.[62]

This basic knowledge of biology, however, was at once insufficient and less adaptable to the group's activities. For example, Endo had some experience in virology but not in bacteriology, yet the group decided to work on diseases caused by bacteria. In addition, members' education did not seem to have any bearing on the group's approach to bioweapons development. Court documents indicate that Endo did not do preliminary research before engaging in weapons development. For example, there is no evidence that when group guru Asahara ordered Endo to isolate botulinum bacteria he first investigated the bacteria and its cultivation process before proceeding. Instead, he went to a lake where he thought the bacteria might be found, and collected soil and water samples to isolate the bacteria from nature.

Not surprisingly, these attempts were unsuccessful. *Clostridium botulinum* is indeed a difficult bacteria to work with. Among the eight existing serotypes of botulinum, each including about one hundred strains, only four contain strains that produce toxins; and among these, only one produces a good number of potent toxins.[63] Therefore, it would have been surprising if Endo had succeeded in isolating a toxin-producing strain from random samples of soil and water, however long he worked at it.

The group also did not seem to grasp the difference between *Clostridium botulinum* (the bacterium that produces the toxin) and the toxin itself. Japanese researcher Katsuhisa Furukawa speculates that group members might have assumed that releasing the bacteria would cause an automatic discharge of the toxin.[64] Group members later testified that three years after starting work on botulinum, Endo was still trying to isolate a strain of *Clostridium*

botulinum. When the work with botulinum did not succeed, the group moved on to anthrax. But after failing to steal a strain of anthrax, the group turned to a sympathizer, who was able to obtain only a common animal vaccine strain, useless for weapons work.

Very much like the Iraqi and South African examples, with little knowledge on which to rely, Aum members had a steep learning curve to overcome. Acquiring the missing expertise would require a stable and continuous work environment, allowing for the steady accumulation of knowledge. Aum's organization and management style, however, created a discontinuous research process and a fragmented work environment.

VERTICAL STRUCTURE, AUTOCRATIC DECISION MAKING, AND COMPARTMENTALIZATION

Aum's structure was founded on a vertical hierarchy, in which decisions were made by its uppermost echelon: Shoko Asahara and his inner circle decided which biological agents to pursue and established time frames for completion of the work. These decisions, however, were based less on scientific and technical feasibility than on Asahara's irrational beliefs. For example, decisions to work on botulinum and anthrax were based on the belief that these were the most dangerous biological agents, a conviction Asahara and his inner circle gained from questionable literature, some of which was literally science fiction. Deadlines for work completion were just as unrealistic. When, in the spring of 1990, Asahara ordered his followers to develop botulinum toxin, he had plans to disperse the preparation in the Tokyo area in mid-April of the same year, giving Aum's members only weeks to achieve the stated objective.[65]

Asahara's orders were not subject to discussion or debate, and his followers practiced the habit of strictly following his directives, notwithstanding their own expectations that some projects were doomed to fail. Those who appeared to have moral qualms about the organization's criminal activities were executed, tortured, or isolated.[66] Asahara also had the habit of changing positions quickly—starting a project and abandoning it, or moving its personnel to another endeavor. Scattered thinking was also common among his lieutenants. For example, his minister of science and technology, Hideo Murai, who was responsible for the WMD program, launched several weapon ventures simultaneously, such as the development of nuclear, laser, and plasma weapons; ballistic missiles; and even a machine to generate earthquakes. None of these weapons materialized.[67]

Not surprisingly, the program was highly compartmentalized. Only members of the inner circle, who managed and conducted the work, had knowledge of the group's bioweapons activity. Access to work areas was strictly regulated.[68] Communications were restricted, and the indoctrination and isolation of group members from the outside world further reduced the pos-

sibility of leaks. Court documents indicate that cult members gave very different statements about the achievements, time frame, and equipment used in the bioweapons program. For example, some members reported that work on botulism ended in 1990, while others stated that the work resumed in 1993; still others suggested that it continued until 1993 without a break.[69] Cult members' opinions also differed as to what was produced, how much was produced, how many individuals were involved, and what each person did.[70] Aum's isolation and need for covertness also limited opportunities to use outside sources of know-how in its biological program. The group strove toward self-sufficiency, acquiring independently—or producing in-house—resources they could have obtained more quickly outside. Similarly, the group produced their own fermentors and aerosol sprayers, the latter of which repeatedly failed to work properly.[71]

DISCONTINUOUS AND CONFLICTUAL WORK ENVIRONMENT

The recurrent turnarounds and scattered work agenda that characterized Aum's decision-making process created an unstable environment that prevented cult members from working long enough on a project to make any progress. Discontinuity in the work environment was also caused by multiple interruptions to Aum's operations due to threats of police investigation.[72] For example, complaints by the local population to the police in 1993 forced Aum to move its biological operations from its headquarters in Tokyo to a location near Mount Fuji.[73] And in 1995, a few months before the sarin attack on the Tokyo subway, the group halted its activities at Mount Fuji because of neighbors' complaints and moved related equipment and documents to an undisclosed location, while also destroying some of their agents.[74] In another example, the group temporarily halted work on botulism because a policeman saw cult members disposing of the failed botulinum culture in a river.[75]

Rivalries between members of the inner circle also contributed to work discontinuity. Asahara cultivated these rivalries, possibly believing that competition between his lieutenants would produce faster results. Instead, competition precluded useful collaboration, while the compartmentalization of the program permitted Endo to more easily hide the sources of his failures. Moreover, due to the possibly lethal repercussions, failure was not an option, giving members another reason to fake results or hide failures. For example, in spite of Endo's not being able to isolate a strain of *Clostridium botulinum* and having obtained a strain of anthrax that was innocuous, he nonetheless convinced his colleagues that he had produced and disseminated some sort of preparation. Group members testified that in 1990 Endo and his team sprayed what they thought—or pretended—was botulinum on the Japanese Parliament, the Imperial Palace, and the U.S. embassy in Tokyo. Endo also poured some of the mixture in a river that flowed to a

water filtration plant; however, the liquid suspension was too thick to aerosolize and fell to the ground after release.[76] Had the mixture contained botulinum toxin, the characteristics of the liquid would have prevented any contamination. Similarly, the anthrax preparation that Endo produced and attempted to release on several occasions was too thick and sticky to aerosolize.[77] The benign compound also clogged the sprayers designed by group members.[78]

Similarly, the cultivation plant established by Murai seems to have had its own share of failures. Court documents indicate that the fermentors used by the group were contaminated with saprophytic bacteria, which would have compromised their results had they been able to acquire and sustain a potent strain.[79] Endo himself declared that little of what he had done succeeded: "Whatever I did, I kept failing. I was an inferior researcher."[80] His rivalry with Masami Tsuchiya, who headed the chemical weapons program with greater success, only reinforced his insecurities, leading to further tightening of security around his own work to hide the poor results. And because heavy compartmentalization precluded formal technical reviews, these barriers to successful outcomes could only be identified at a very late stage.

Very limited information transpired from the trial regarding how Aum organized the workflow of its biological program. In the botulism project, for example, the group had placed its different stages under the responsibility of different members of the inner circle: Endo was responsible for isolating the bacteria; Murai was in charge of the cultivation process; and another inner circle member, Fumihiro Joyu, was responsible for developing the spraying device. Reportedly, more than ten people were engaged in this effort.[81] Considering the rivalries within Aum's higher echelons and the group's violence toward its members—as well as its obvious failures—the likelihood that the different stages of any project were coordinated or integrated is very slim.

In the end, Aum failed at every stage of the biological weapons life cycle. It lacked the full range of expertise needed to isolate, manipulate, produce, and aerosolize the bacterial agents it selected to work on. Aum's organization and management style interfered with or entirely precluded the necessary coordination and integration essential to successful group work. This ineffectual environment sharply reduced the group's ability to overcome the stiff technical difficulties associated with biological cultivation, scaling up, and dissemination. It also precluded the use of technical expertise from outside the inner circle, including from among the cult's lower ranks, let alone from outside the cult itself, making problem solving virtually impossible.[82] Discontinuity in the scientific process also prevented Aum's personnel from working long enough on any one project to accumulate knowledge and make progress. In the end, Aum's inability to develop biological weapons led Asahara to speculate that U.S. assessments of the risk of biological

terrorism were designed to mislead terrorist groups into pursuing such weapons.[83]

The Iraqi, South African, and Aum Shinrikyo bioweapons cases illustrate the difficulty for covert state and terrorist group programs to create the combination of exogenous and endogenous variables that foster progress, particularly in the absence of a sufficient knowledge base at the start of these programs. Indeed, the requirements of knowledge creation directly contradict those of covertness. The free flow of information, unrestricted interactions, and openness to the outside world, which supported scientific progress in the American bioweapons program, would have put these covert programs at greater risk of detection, due to the increased number of people knowledgeable about the program, and the greater opportunities for penetration by foreign intelligence or police enforcement agencies. The establishment of integrative and coordinating mechanisms, essential to ensure the successful passage from one stage of a bioweapon's life cycle to the next, would also have exposed the program to detection by increasing the number of individuals with broad knowledge of it. Therefore, the three programs adopted a suboptimal organizational model, similar to that of the Soviet model, which restricted information flow; limited integration and coordination; and, in the process, adversely affected overall progress—even precipitating program failure altogether.

The autocratic and coercive character of the three programs' management styles created multiple perturbations that led to discontinuity in scientific work. Coercion also prevented the creation of a work environment that would have allowed individuals to trust one another, flag problems, and discuss them openly at an early stage—an essential part of the learning process. Instead, failures were stigmatizing events that needed to be hidden for fear of retribution, which nurtured a culture of fraudulent behaviors and prevented the creation of a cadre of professionals, which in turn exacerbated the knowledge handicap.

The fact that the three programs discussed here operated in a coercive environment does not mean that all future illicit programs will also face the same violent circumstances. Coercion in the Iraqi, South African and Aum Shynrikyo programs was a bonus that made the existing challenges of bioweapons development even more daunting. However, as long as biological weapons are banned, future illicit programs will face similar organizational and managerial constraints imposed by covertness. These observations have important policy implications, the subject of the next chapter.

CHAPTER 7

Preventing Bioweapons Developments

Policy Implications

In the case study chapters, we have observed how endogenous and exogenous characteristics of a bioweapons program can facilitate or hinder its development. Although access to material resources is important, it is the combination of organizational, managerial, political, and economic circumstances characterizing a program that ultimately affects its ability to produce and use knowledge, and thus affect the pace and ultimate program output. These case studies also offer an interesting gradation of variables and illustrate the importance of analyzing their effects as they interact to achieve a realistic assessment of a program's outcome. More importantly, the case studies underscore how difficult it is to produce working bioweapons, however vast and resourceful the program. The fragility and unpredictability of microorganisms require that state and nonstate actors create meticulous organization, management, and sustained coordination of all the actors affecting a program over time, not only to permit success in the laboratory but also to transform a laboratory sample into an agent that can survive scale-up, weaponization, and delivery. These ideal conditions are difficult to achieve under any circumstances, let alone those surrounding the constraints of maintaining covertness—particularly under autocratic and violent regimes. The bioweapons proliferation puzzle, therefore, is not a straightforward input/output process, in which access to material resources automatically produces a working weapon. It is instead a sustenance challenge, which requires solving a complex, interactive, and long-term set of social and technical problems involved in controlling the unpredictability of living biomaterial, as well as coping with the messy combination of endogenous and exogenous variables.

These findings have implications at four important levels. First, they have an impact on national and international security by suggesting a new narrative about bioweapons developments that has greater dissuasive power to those who might seek this technology than does the current technology-

based discourse, which emphasizes ease of development and accessibility of resources. Second, they underscore the importance of strengthening the Biological Weapons Convention (BWC) and call for a review of current nonproliferation and counterproliferation policies. Third, they offer new insight on how to achieve more accurate threat assessments of suspect state or terrorist programs and design more tailored responses to these threats. Finally, they question the design of current policies aimed at limiting the spread of knowledge as well as the widely shared belief that new technologies will erase the hurdles associated with bioweapons developments.

Bioweapons Dissuasion

In 2001, several memos written in 1999 by al-Qaeda deputy head Ayman Al Zawahiri were found in Afghanistan. They revealed that the group had considered biological weapons development because "the enemy drew our attention to them by repeatedly expressing concerns that they can be produced simply with easily available materials . . . [and that] defense against such weapons is very difficult, particularly if large quantities are used."[1] If a conventional narrative message about the ease of bioweapons development persuaded al-Qaeda to pursue such a course of action, it could surely convince other groups or states to do likewise. Yet the narrative did not change after these revelations. Instead, it was brought to a much higher pitch during the administration of George W. Bush, and although the Obama administration has toned it down a little, it continues to emphasize the low barriers to entry in acquiring bioweapons.[2]

When the WMD Commission, chartered by Congress in 2007 to evaluate the WMD threat, published its findings in 2008, its final report, titled *World at Risk*, encapsulated the whole set of beliefs and assumptions made about bioweapons. In its transmittal letter to President George W. Bush, the commission stated that its intention was not to frighten or reassure the American public but to "convey the sobering reality that the risks are growing faster than our multilayered defenses. Our margin of safety is shrinking, not growing." The report reiterated the long-held belief that due to the dual-use nature of biological material and technologies, and the fast pace of biotechnology advances, little could be done to prevent bioweapons proliferation. This was particularly so because bio-agents are not sufficiently well secured throughout the world, including in the United States, despite U.S. efforts in this field during the past decade. The report also underscored U.S. vulnerability to bioweapons use by showing that in spite of U.S. investments in preparedness and response, the country would be overwhelmed even by a low-scale bioterrorism event. As a result, the report predicted that a terrorist event involving a weapon of mass destruction would likely take place somewhere in the world by 2013.[3] The report provided no details

about what led its authors to settle on a five-year time frame for an attack, but the commission believed that terrorists are more likely to obtain and use a biological rather than a nuclear weapon.

Although the report epitomizes the current discourse about bioweapons development, the narrative's origins predate 2001 and have been fleshed out by four successive administrations. Already in the mid-1980s, Deputy Assistant Secretary Douglas J. Feith stated in testimony before Congress that bioweapons development is fast and straightforward, particularly with the advent of new biotechnologies.[4] President Clinton and officials in his administration, along with several security experts, took the narrative further by popularizing the idea that bioweapons development involves nothing more than the accumulation of three widely available ingredients—material, equipment, and scientific information.[5] The 2001 anthrax event gave new traction to the narrative and propelled it to the level of collective consciousness: the bioweapons threat is at once palpable and inevitable, and could emanate quickly and easily from a covert state program, terrorist group, or even a disgruntled lone wolf.[6]

Both the George W. Bush and Obama administrations have endorsed and designed policies that have resulted from this narrative. Operating from the premise that bioweapons use is virtually inevitable, these policies focus on increasing preparedness and response to bio-events. Since 2001, the United States has spent more than $60 billion on biodefense programs designed to detect the release of harmful agents (the BioWatch program), produce medical counter-measures (the Bioshield program), create stockpiles of drugs and vaccines, increase research on a set of agents deemed most likely to be used in a bio-attack (the so-called Select Agent List), and strengthen laboratory security.[7] The Bioshield and BioWatch programs have been harshly criticized: after a decade of effort, the former did not produce any new vaccines, while the latter has experienced repeated false alarms in its network of biosensors deployed in major cities, and still requires the physical removal of filters for analysis in the laboratory, which can take several days.[8] In spite of this, the Obama administration in 2013 requested an increase in BioWatch funding, which could potentially bring its total cost to over $3 billion in the next five years.[9]

The tightening of laboratory-security regulation has also been criticized for making scientific work overly cumbersome, costly, and less efficient due to restrictions on personnel and information exchanges,[10] while the multiplication of laboratories working on select agents poses a potential security threat due to the inability of the federal government to inventory all of them and their research.[11] Although the Obama administration has placed more emphasis than had the Bush administration on the threat of natural outbreaks of infectious disease,[12] it continues to prepare for mass-casualty bio-events, as demonstrated by its recent acquisition of costly antivirals to treat smallpox. Many experts have criticized the latter decision as unnecessary,

because the United States already possesses a stockpile of smallpox vaccine sufficient to protect the whole U.S. population in the unlikely event of a large-scale smallpox attack.[13]

Finally, new emphasis was placed on restricting the spread of scientific results believed capable of helping terrorist groups develop bioweapons. In addition to the H5N1 "bird flu" experiment controversy of 2011, described at the beginning of this book, there have been more restrictions on scientific information. In December 2013, California state officials, after consultation with federal officials, announced the removal of genetic sequencing information for a new strain of botulism from a paper that was previously published in the *Journal of Infectious Diseases* in October 2013. The California Department of Public Health discovered the new strain as a result of a natural infection, but fears that terrorists might attempt to reproduce the strain prompted the withdrawal of the data, at the risk of undermining the ability of other public health agencies to respond adequately to a future natural botulinum infection.[14] As a result, the current biothreat narrative and its policies, with their highly publicized shortcoming and failures, have reinforced the belief that the United States and its allies are not prepared to respond to a bio-attack in spite of a significant investment in funds and efforts over the past decade, and therefore remain very much vulnerable to such attacks. Rather than dissuading an adversary, this narrative only reinforces the desirability of developing bioweapons.[15]

Since 2001, WMD dissuasion has been a key element of successive Quadrennial Defense Review (QDR) reports (2001 to 2010). Each QDR emphasizes the importance of dissuading adversaries from embarking on programs that could threaten the United States and its allies. In these documents, dissuasion is defined as taking action to decrease the benefits or increase the cost of such weapons, thereby creating strong barriers to entry.[16] Regarding bioweapons, none of these objectives have been achieved: the current biothreat narrative presents a cost/benefit ratio in favor of developing bioweapons, and its concomitant policies have not addressed the real barriers to entry in the bioweapons field—the acquisition of expertise and its determinants.[17]

This book suggests a new narrative that is more likely to dissuade potential proliferators from entering the field. The key message to convey is that bioweapons developments are not only difficult but highly uncertain. The fragility and unpredictability of living microorganisms creates a natural barrier that is challenging to overcome without the appropriate expertise, as demonstrated by the Iraqi, South African, and Aum Shinrikyo cases. The acquisition of expertise is therefore the key barrier, which is overcome not simply by means of acquiring scientific documents but through prolonged hands-on experimentation, requiring the cooperative work of a community of experts open to the outside world, who have expertise adapted to the types of agents under study and the skills required to move a natural agent

through the various stages of research, development, production, and weaponization. Creating such a knowledge base can take decades and ultimately still fail, as shown by the Iraqi and South African programs. The third hurdle lies in creating the proper organizational, managerial, and social conditions that foster knowledge creation, transfer, and institutionalization while also managing external factor—a difficult process, as seen in both the U.S. and the Soviet cases. Further, developing bioweapons while operating under the constraints of covertness not only imposes additional costs to create the protective layers necessary to prevent detection but also complicates the already stiff challenges of knowledge management. Finally, the lingering question remains whether or not biological weapons are feasible or at all practical. After decades of work and hundreds of millions of dollars spent, U.S. and Soviet bioweapons scientists could not convince the military authorities they served that the bioweapons they had developed would work reliably and predictably due to their sensitivity to environmental conditions. And even with substantial resources, Aum Shinrikyo could not develop a crude bioweapon. Rather than promoting a sugarcoated picture of how easy bioweapons are to make and operate, the real truth ought to be acknowledged about two realities: first, the story about past programs, state and terrorist groups alike; and second, the enduring conditions that such living organisms must confront to achieve survival and success. These realities should form the new bioweapons narrative.

Revisiting Current Nonproliferation/Counterproliferation Policies

One of the gravest consequences of the biothreat narrative has been to focus attention and nonproliferation policies almost exclusively on frustrating material procurement. To be sure, these policies, including export control and UN Resolution 1540, are essential elements of nonproliferation and should be continued. However, material resources are not the key barriers to bioweapons development. It is important, therefore, to reorient current and future policies toward preventing the acquisition of expertise. Since proximity, direct contact between scientists, cooperation, and the stability and continuity of scientific work are essential to scientific progress, nonproliferation and counterproliferation efforts should focus on disrupting these factors.

NONPROLIFERATION VALUE OF A BWC VERIFICATION REGIME

The BWC is an essential nonproliferation tool, not only because of its undeniable normative value but also because it can be used to directly impede knowledge acquisition. But to fully use the nonproliferation power of

the BWC, the international community must revive the idea of a formal verification mechanism to the treaty.

The treaty's lack of a verification mechanism has thus far obstructed its implementation and allowed member states—such as the Soviet Union, South Africa, and Iraq—to continue or launch their programs soon after signing the treaty. To remedy this gap, BWC member countries negotiated in the late 1990s a legally binding inspection regime—known as the BWC Protocol—that was submitted for adoption in 2001.[18] Unfortunately, the U.S. government rejected the protocol, arguing that the BWC is unverifiable and that the inspection regime would unfairly target U.S. pharmaceutical and biodefense facilities, allowing potential adversaries to acquire industrial secrets or compromise U.S. biodefense efforts.[19]

The protocol as submitted in 2001 proposed the creation of an international organization responsible for the implementation of the BWC, requiring states to declare past and present bioweapons and biodefense activities and facilities, and establish an inspection regime.[20] The inspection regime was surprisingly nonconstraining: random and clarification visits were to be held, with a fourteen- and seven-day advance notice, respectively.[21] This would have given U.S. pharmaceutical companies and biodefense facilities ample time to protect their secrets. It would have also possibly permitted proliferators to hide their illicit activities. This last argument has undeniably worked against the adoption of the protocol.

To be sure, the verification measures as proposed in 2001 would not have caught a proliferator red-handed. But the value lies in their ability to disrupt the continuity of bioweapons work and delay progress. Recall that international inspections were quite successful in disrupting Iraq's bioweapons efforts. In anticipation of UN inspections in 1991, Iraqi authorities ordered the destruction of bulk agents, a thorough cleanup of several facilities, and the destruction of equipment and bombs.[22] Similarly, pending inspections under the Trilateral Agreement signed in 1992 between the United States, Britain, and the Soviet Union prompted Soviet authorities to stop bioweapons work at several facilities, scrub them clean, and destroy some equipment.[23] Similar outcomes were achieved in the nuclear and missile fields, in which the fear of international inspections had even prompted program cancellation. In Iraq, for example, possible UNMOVIC inspections prior to the 2003 war caused Iraqi authorities to completely shut down its covert Jenin cruise missile program to avoid detection.[24] In a similar move, Iranian authorities are believed to have ordered the destruction of an undeclared nuclear facility at Lavizan, near Tehran, sometime between August 2003 and March 2004, fearing that UN inspections might result in tougher sanctions.[25]

Thus, interruptions caused by inspections, or their expectation, can set back ongoing experiments or development work, particularly when they

occur at sensitive stages. This is especially so during the knowledge accumulation phase, when teams have not jelled yet and their knowledge is still uncertain, or during production, which can cause the destruction of fragile viruses or bacteria. Changes to experimental protocols are done on the fly, and if they are not recorded, they may be lost in the confusion of a move, a temporary interruption, cleanup, or the hiding of documents and materials, thus preventing staff members from resuming work where they had left off. If the interruption is long lasting, knowledge can be lost for good, as demonstrated in the case of the Trident warhead component known as Fogbank, discussed in chapter 2: the foam could not be reproduced, and it required almost a decade to create a replacement. Therefore, the absence of a BWC inspection regime deprives nonproliferation efforts from a powerful tool. It is essential to resume discussions about the BWC protocol or a similar regime.

COUNTERPROLIFERATION OPTIONS

In the meantime, several counterproliferation options can be used to frustrate bioweapons development by states and terrorist groups. Disruptions of a program's scientific stability and continuity can be achieved in several ways. Similar to pending inspections, the threat of military or police operations in nearby areas can keep the suspect country or group permanently fearful of detection, obliging the program to move repeatedly, conceal its activities, or stop work entirely, if only temporarily. For example, in 1993, townspeople residing in the vicinity of Aum Shinrikyo's headquarters in Tokyo complained to the police of a foul smell emanating from the building, which forced Aum to move its biological operations from Tokyo to a location near Mount Fuji.[26] And in 1995, a few months before the sarin attack on the Tokyo subway, the group discontinued its bioweapons activities at Mount Fuji because of neighbors' complaints and moved its equipment and documents to an undisclosed location, while also destroying some of the material it had produced.[27] Thus, the mere possibility of police intervention disrupted Aum's biological activities and hampered its already compromised bioweapons program. Similarly, in his 1999 memos, al-Qaeda's al-Zawahiri directed his followers to periodically move their WMD efforts to avoid detection.[28] Finally, possibly fearing military action, Iran is also reported to have temporarily canceled work on a nuclear warhead after U.S. forces invaded Iraq.[29]

Second, sabotage, a strategy used in the past to target equipment, can also effectively disrupt scientific work. For example, Iran is believed to have suffered technical delays at its Natanz facility due to the sabotage of some of its equipment by Israeli and U.S. intelligence operatives.[30] The Stuxnet computer worm has also caused several centrifuges to malfunction, a disruption believed to have caused a two-year delay in Iran's nuclear program

advancement.[31] Sabotage can be particularly damaging in the bioweapons field to the extent that it affects production and scale-up equipment. Equipment malfunction during these stages not only halts the accumulation of knowledge when theoretical concepts are tested during production but also could destroy a batch of bacteria or viruses undergoing production. Both outcomes would result in major program delays.

Disrupting team composition can also produce program delays and knowledge loss. Because teams take a long time to jell and work effectively, forcing changes in their composition can disrupt cohesiveness and delay work, as well as foment distrust among members, particularly in the context of a hostile environment. Thus, finding ways to generate competition and conflicts within a program or raise suspicions among team members can effectively decrease their willingness to exchange information, cooperate, and transfer their tacit knowledge. Such mutual distrust can be achieved simply by spreading rumors of the existence of a mole within the program or the possibility of a defection. According to press reports, Israeli authorities have in the past few years conducted targeted assassinations of Iranian nuclear scientists with hopes of disrupting the Iranian nuclear program. Aside from the fact that such a strategy is morally repugnant, targeted assassinations can backfire. The remaining scientists may become more loyal to the regime or to the program in memory of their fallen friends or because of the innocents who were the unintended victims of such eliminations.[32] Program delays would be more effectively achieved by making the suspected government become the object of scientists' ire. For example, fear of outside exposure or defections can prompt the government to increase repressive measures and raise security barriers to control the flow of information and scientific exchanges. In the Iranian nuclear program, for example, authorities responded to the defection of several nuclear scientists and government officials by tightening controls over program personnel, limiting their access to information, and arresting several individuals to discourage future defection or double-agency.[33] As noted in chapter 2, similar developments occurred in the U.S. nuclear program after revelations surfaced in 1999 that Chinese American computer scientist Wen Ho Lee had taken a disk containing nuclear codes out of Los Alamos. The fear that he might have transferred the codes to China—proven unfounded later—led to a change in the laboratory's management and the reinforcement of security measures. Personnel were subject to numerous FBI interviews and polygraphs, and some were summoned in the middle of the night for interrogation. The military discipline imposed by the new director at Los Alamos, coupled with the introduction of a for-profit contractor to manage the Los Alamos and Livermore laboratories, alienated the scientific staff and created disruptions in scientific work, ultimately causing a decrease in scientific output and the departure of staff.[34] Defections can also lead to revealing the existence of previously unknown facilities. Iraq, for example, provided new details and

documents about its bioweapons activities to UN inspectors after Hussein Kamal defected to Jordan in 1995.[35] Similarly, the defection in 1989 of Vladimir Pasechnik prompted Soviet authorities to be more open with Western powers, which eventually led to Soviet acceptance of mutual visits.

Playing on a program's fear of detection or a mole within the organization can also constitute an efficient strategy to push the program toward an organizational model that limits or altogether prevents communications between knowledge reservoirs. The reactions of authorities to possible defections in Iran's case or to a spy at Los Alamos in the U.S. case are particularly enlightening from this standpoint. The increased security effectively raised new barriers to cooperation, limiting tacit knowledge diffusion within the program. In such a context, communal knowledge will particularly suffer, due to decreased collaborations within the program and reduced access to outside expertise, compelling staff members to rely on their own individual—and more limited—knowledge. This impedance to communication has the advantageous consequence of making problem solving more difficult and therefore slowing down progress. Compelling the suspect program to locate the various stages of a bioweapon's life cycle at different sites and limiting connections between them can further reinforce organizational impediments. The threat of police or military activity and the possibility of international inspections can be equally effective at compelling the suspect group or country to retreat to an adverse organizational model that shatters a program into pieces, spreading it to different locations while compartmentalizing its component parts. With reduced direct interactions, the transfer of tacit knowledge and task coordination are compromised.

Although such counterproliferation policies cannot stop an existing program, they can slow its progress and perhaps make advancement so difficult that the country or group will eventually reconsider its plans. If nothing more, such delays offer time for additional policy options. If they are combined with a formal inspection regime, their disruptive power would be greatly increased. The effectiveness of both counterproliferation measures and formal inspections would be especially strong when applied during the weakest stage of a bioweapons program: the knowledge accumulation or exploratory phase, when teams are still learning about and experimenting with various agents and processes. Suitably targeted, these policies can also handicap key transition stages of a bioweapons life cycle (for example, during scale-up of fragile microorganisms). These approaches also have the virtue of providing options other than military intervention or targeted assassinations, which can produce severe negative consequences.

A New Threat Assessment Template

To the extent that the variables discussed in this book affect bioweapons programs differently, nonproliferation/counterproliferation policies should be adapted to the specific circumstances of the suspected programs. This requires a threat assessment model that accurately identifies the development stage of a program and its speed of progression. Thus far, the U.S. intelligence community has had a dismal track record in accurately assessing past bioweapons programs, alternately over- or underestimating the bioweapons threat.[36] Here, too, better assessments could be achieved by redirecting the focus from tracking procurement of material by state and nonstate actors to data collection and analysis on the variables that affect knowledge use.

The starting point of any bioweapons threat assessment should be an evaluation of the potential for a state or terrorist group to manipulate and process successfully fragile microorganisms. To that end, data collection and analysis efforts should first of all attempt to determine whether the individuals involved have sufficient knowledge. The case studies discussed in the previous chapters show that roughly three categories of individuals may be involved in a nascent bioweapons program: the novice, the sub-expert, and the expert.[37] A novice is a person with a generic educational background in the discipline but no specific or practical expertise. Aum Shinrikyo's program was staffed with novices. The sub-expert is a person with a specific expertise—say virology or bacteriology—and advanced theoretical knowledge but no practical expertise in developing biological weapons. Most scientists in the Iraqi and South African programs belonged to this category. The expert is an individual with advanced theoretical knowledge and practical expertise in a domain directly applicable to bioweapons work, and possibly even bioweapons expertise. The American and Soviet programs both included this category of scientists.

These distinctions are important because they reveal how different people learn and use their knowledge—that is, what their absorptive capacity is and, consequently, how quickly their work progresses. For example, because they exercise their knowledge repeatedly and in different contexts, experts possess a more expansive library of cases and situations that allow them to identify subtle differences between similar situations and find more appropriate solutions to the problems they face. Sub-experts, on the other hand, lack the expert's practical experience and therefore must analyze each event explicitly, make many inferences, and take longer to evaluate a problem and seek a solution. The process is more arduous and lengthy for novices, who do not have the practice or the theoretical and specialized knowledge of the expert and sub-expert. Unable to assess the problem accurately, they tend to spend more time looking for solutions than assessing the problem.[38] The level of expertise also determines a scientist's/technician's ability to use outside assistance or technology and adapt it within his

or her own context. Therefore, the lower the starting knowledge/skill base and the corresponding absorptive capacity, the slower the progress and the more difficult the use of outside expertise and equipment will be.[39]

Second, because expertise in one domain does not necessarily transfer to another domain, it is important to investigate whether individuals working in a bioweapons program have expertise that corresponds to the actual work they are doing, and whether the program has access to the whole gamut of knowledge required to ensure passage from one stage to the next in a bioweapons life cycle. An expert in virology, for example, will not necessarily be able to readily apply her knowledge to work with bacteria, which behave very differently from viruses. Similarly, knowledge of anthrax bacteria may not be directly applicable to work with plague bacteria. Therefore, the further removed the resident expertise is from the work being conducted, the more difficult and lengthy is the acquisition of knowledge. In this context, even experts in one discipline might have to take the same learning path as sub-experts or novices if their expertise does not fit the work being conducted. If one has familiarity with one type of biological organism, this can help facilitate some aspects of the learning process, but it will not eliminate the need for trial-and-error experimentation on the new organism. Similarly, because stages of a bioweapons life cycle require the intervention of different disciplines and skills, lack of knowledge in one stage can substantially delay a program in another, or prevent further developments altogether.

Organization at the program and facility levels is also important to consider because it determines what *type* of knowledge is created. Programs and facilities that limit collaboration tend to promote individual rather than communal knowledge. In contrast, programs and facilities that promote communal knowledge are likely to advance faster and produce better results than will facilities that promote personal knowledge, where scientists work in isolation, because communal approaches allow the use of a whole pool of expertise. Integrated contributions by individual scientists, available to all, create a knowledge that is greater than the sum of individual expertise. Thus, a team of sub-experts with a flat organizational structure may progress faster than a team of experts with a vertical structure, as demonstrated by the cases of Vector and Obolensk in the Soviet Union. A team of novices operating in a vertical organizational structure will be unlikely to advance, as was the case for Aum Shinrikyo.

A bioweapons program cannot progress rapidly if its interdependent stages and functions are not coordinated and integrated. The division of labor resulting from the involvement of different disciplines and skills inevitably fosters barriers between people. Organizational division and work structure can also foster additional impediments, especially if a program is more concerned with ensuring covertness than creating the conditions for knowledge production and transfer. Yet case studies have shown that some

of these barriers can be reduced by the development of integration mechanisms. Therefore, data collection efforts should strive to determine whether and what type of integration mechanisms have been designed at the program and facility levels to ensure knowledge sharing. At the program level, for example, it would be important to clarify whether a program benefits from a heterogeneous engineer. This key figure ensures the long-term sustainment of financial and leadership support for the program, as well as its leadership's awareness of its technical, financial, and time constraints, so that objectives set at the highest level are in tune with the program's capabilities. System engineers—individuals responsible for seeing a project through from inception to culmination, and synchronizing the work performed by different divisions and individuals—are also essential integration tools that can operate at both program and facility levels. Most importantly, heterogeneous engineers and system integrators help create a stable and continuous work environment—an essential condition of knowledge accumulation—by limiting the effects of disruptions due to fluctuations in funding, political support, and changes in personnel, among others.

Data collection efforts should also attempt to determine whether mechanisms such as functional overlap and transition teams have been integrated into the work organization within and between facilities performing different stages of a bioweapon's life cycle. Both mechanisms help fine-tune the coordination of upstream and downstream stages, facilitate the transfer of tacit knowledge, and aid successful passage from one stage to the next.

To the extent that information about knowledge, organization, and integration can be gathered, it is important to identify potential development scenarios in order to project different outcomes and timelines, and identify program weaknesses. For example, if a suspect bioweapons program is composed of novices with no relevant knowledge, a vertical organizational hierarchy, and no integration mechanisms, it is likely that it will make no progress. If, on the other hand, its organizational model changes in favor of a horizontal structure and includes some integrative mechanisms, its chances of faster knowledge acquisition are increased. Yet even in this scenario, the knowledge base is so low that the learning phase will likely be extended and the chance of success very much delayed. This allows more time to design adapted policy responses to this problem. At the other extreme, if a group of experts representing some but not all of the expertise required for bioweapons development operate in a vertical structure with some integrative mechanisms, the chances of successful outcome at a more rapid rate are increased, as is the urgency of developing appropriate policy responses.

A deeper understanding of a program's capabilities and timeline could be achieved by collecting data about other important variables that affect knowledge transfer, such as the political and economic context in which a program is taking place, its management style, and its prevailing social context. For example, if disagreements between political figures or agencies

over a program are detected, nurturing these disagreements can have a powerful disruptive effect, as was the case in the U.S bioweapons program. But even the sketchy picture of a program distilled from a focused analysis of what constitutes the hinges of a program—knowledge, organization, and integration—can serve as a solid base for producing an insightful assessment of a program's status and advancement. That alone would offer intelligence and policy practitioners the basis on which to develop adapted and more effective policies than depending on material procurement alone.

Preventing the Spread of Knowledge and the Role of New Biotechnologies

Although some nonproliferation initiatives have attempted to tackle the issue of knowledge transfer, their main failure has been to inadequately assess what type of knowledge can support bioweapons work. Brain drain prevention projects under the Cooperative Threat Reduction (CTR) Program and current oversight of dual-use research are two examples. It might seem odd to discuss brain drain prevention and current efforts at restricting publications of scientific research under the same heading. Whereas the first has obvious nonproliferation benefits—preventing the spread of bioweapons-related expertise—the second has been sharply criticized for impeding the spread of scientific data that can benefit public health worldwide. Yet both contribute to the same objective: preventing state and nonstate actors from benefiting from previous bioweapons work or dual-use research. They also face similar challenges in their design due to misconceptions about what constitutes knowledge of concern. Similarly, the current debate about the role of the so-called biotechnology revolution in speeding the spread of expertise and facilitating bioweapons development is based on the mistaken assumption about what constitutes expertise and what new technologies can actually accomplish.

BRAIN DRAIN PREVENTION PROGRAMS

Brain drain prevention programs were launched in the 1990s as a result of the breakup of the Soviet Union, which unleashed new threats of proliferation of nuclear, chemical, and biological technology, material, and expertise. Spearheaded by the United States, the international community designed and implemented assistance programs to secure weapons facilities and their dangerous material, and offer jobs to weapons scientists to prevent them from offering their services to other states or terrorist groups. The Department of Defense Cooperative Threat Reduction (CTR) Program was and probably remains the largest nonproliferation program in the Soviet Union. Although it first focused on nuclear and chemical proliferation, it expanded its reach to include bioweapons facilities and scientists in the

late 1990s. The program has been quite successful at securing bioweapons facilities and their collections of pathogens, as well as improving the safety of laboratory work at these facilities. It has also effectively eliminated two major proliferation threats of specialized equipment and weaponized pathogens through the dismantlement of the anthrax production plant in Stepnogorsk, Kazakhstan, and the elimination of live anthrax spores buried by Soviet troops in the late 1980s on the Soviet bioweapons test site at Vozrozhdeniye Island.[40] On the brain drain front, however, there remain reasons for concern about the effectiveness of these nonproliferation activities, primarily due to the way brain drain programs are designed and implemented. It is important to take stock of this experience in the Soviet Union because, although the CTR Program is winding down in Russia, the threat has not completely been eliminated: although the bioweaponeer population is aging, there is a contingent of younger scientists in their forties and fifties who might still pose a threat. In addition, the CTR Program continues to operate in other former Soviet states and has expanded its reach to other countries in Africa, Asia, and the Middle East, using the same model. It is therefore poised to make the same mistakes, thereby compromising its nonproliferation value.[41]

Three design flaws have marred the effectiveness of the CTR Program. First, most of the research projects funded under the CTR Program maintain bioweapons scientists at their former facilities, where they work on biodefense-oriented projects that involve many of the same dangerous pathogens that former bioweapons scientists worked on in Soviet times. In addition, these scientists often work with the same Soviet-era colleagues. These two factors allow them to maintain many of the tacit skills and communal knowledge developed under the Soviet bioweapons program instead of facilitating its erosion. Second, the CTR Program is facility based, meaning it only supports scientists working at certain bioweapons facilities. Once these scientists leave their former institutes, either because of downsizing or for personal reasons, they cease to qualify for this support, even though a covert program could advantageously use their expertise. The facility-based approach also has the major disadvantage of not distinguishing between scientists and technicians who might actually pose a threat and those whose expertise would not benefit a covert program. Indeed, CTR assistance is based on self-reporting by scientists, but no attempt is made to verify the information and request details about past work. The sources of this oversight are quite understandable: when the program was launched, the main objective was to open up as many facilities as possible, and at the time, requesting too many details about a scientist's career and past work could have been construed as a form of intelligence collection, which would have effectively doomed the program. As a result, support was provided with little knowledge about the type of expertise, length of work, and potential threat posed by the engaged individuals. Finally, the program focuses on

facilities previously believed to be part of the core Soviet bioweapons infrastructure, at the risk of neglecting facilities located in the other two circles, such as the anti-plague system. Anti-plague scientists may pose as much of a threat as those employed in core facilities, not only because of their long experience working with dangerous pathogens but also because of their experience training other scientists. Because anti-plague facilities were educational institutions, their scientists developed skills that allow them to transfer their expertise more effectively than those who did not have the same training mission.[42]

To become a more potent factor in stanching the proliferation threat of biological weapons skills, the CTR Program should modify its current approach, which emphasizes the expansion of the program to as many facilities as possible, to one that engages the facilities and individuals that pose the greatest threat. Achieving this objective requires gathering information about the organizational and integrative features of the facilities earmarked for engagement. Learning how people worked together in the past—whether they collaborated freely or were constrained by security measures, and whether they were supported by management or pressured to achieve specific results—can illuminate whether the facility produced primarily communal knowledge or individual knowledge. For example, due to its heavy compartmentalization, autocratic management style, and numerous conflicts among scientists, the knowledge created at Obolensk was primarily personal: people worked in isolation or with a small set of individuals. In contrast, Vector produced mostly communal knowledge, due to the management's emphasis on collaboration and information sharing.

Clearly, then, such disparate environments and types of knowledge require different policy responses. In the case of Vector, the CTR approach of relying on keeping scientists at their former facility, working with their former colleagues on pathogens they worked on in their bioweapons work, is completely counterproductive: its main consequence is to preserve the scientists' tacit skills and, more importantly, their communal knowledge. A more effective policy would consist of breaking up the teams. Because communal knowledge is shared by all members of the team, but no one member owns the whole of that knowledge, team breakup is a good strategy for promoting the erosion of communal knowledge over time. Therefore, the proliferation threat posed by Vector scientists could be more effectively dealt with by creating jobs for them at different locations. For example, creating endowed positions in academic institutions or even supporting their retirement might prove to be useful options. On the other hand, because their knowledge is mostly individual, Obolensk scientists could continue working at their former site. In their case, however, the main objective would be to promote the erosion of their individual bioweapons-related skills, which can be achieved by redirecting their work to research and scientific projects that do not involve the dangerous pathogens they worked on in

Soviet times, such as health-related research. In general, the CTR Program should de-emphasize biodefense projects and create incentives for scientists to exit the bioweapons field, in order to reduce the overall number of individuals able to maintain their bioweapons-specific skills.

Second, the CTR Program should aim to gather more data about the personal experience and careers of the individuals engaged under the program. In the late 1990s to early 2000s, conventional wisdom had it that there was a tight correlation between the position of a scientist in the organizational hierarchy and the individual's expertise—and thus proliferation potential. Although some institute directors and laboratory heads of Soviet facilities had wide knowledge or very deep expertise, evaluating threat level based solely on hierarchical status alone is misleading. A more appropriate approach would be to determine the extent of an individual's practical expertise and length of service in the laboratory. Many institute directors and laboratory heads had ceased practicing their scientific skill sets due to their managerial obligations. It is therefore likely that many of them had lost their tacit skills and posed little threat. Others, including technicians, made it a point to continue their laboratory practices in order to maintain their skills and their subordinates' respect, which should have placed them in a higher threat level. In this regard, the devil is truly in the details.

Generally, however, those who pose the greatest threat and deserve CTR attention are the scientists and technicians who routinely practiced their trade. The length of their careers can also provide a more refined assessment of their threat level. For example, a technician who has honed his skills over a twenty-year period can be more useful to a covert program than a scientist with only five years of experience. Similarly, an individual who practiced at different facilities over time, or served in an integrative capacity, likely accumulated skills from different facilities, thereby achieving a broader set of expertise. In the Soviet context, due to the culture of false reporting, it is also important—information permitting—to distinguish between scientists who faked their way through the system and probably accumulated little threatening knowledge, and those who acquired and routinely practiced skills that could be valuable to covert programs.

Third, the CTR program should switch from a facility-based to an individual-based approach. This would allow continued support to key bioweapons scientists, even if they should depart their former facilities. Finally, the criteria used to identify the facilities that should receive support needs to be expanded to include not only the type of past weapons activities but also the staff's training capabilities. The information required to make such determinations can be readily obtained: although the Russian government has imposed increased restrictions on exchanges with foreigners, most scientists can still talk about their Soviet-era work organization, social context, and personnel/management relationships without divulging technical details regarding their former bioweapons research. They also often discuss

the length of their careers and the type of work they did, particularly with foreign colleagues who speak the same technical language. Whether a scientist has faked his way through the system or actually performed can also be discerned through cooperative research projects: peers can readily judge whether a scientist possesses actual skills.

Armed with a better understanding of knowledge management, organization, and integrative mechanisms, policymakers could develop policies better suited to the type of threat existing at specific facilities or posed by specific individuals. The current cookie-cutter approach of the CTR Program does not take into account these distinctions and, more importantly, often preserves the threat instead of eliminating it.

RESTRICTIONS ON SCIENTIFIC PUBLICATION AND THE ROLE OF NEW BIOTECHNOLOGIES

The H5N1 controversy of 2011, and the recent removal of genetic information from a scientific journal about a new strain of botulism by California state authorities, illustrate the belief that replication of scientific work can be achieved by resorting to scientific publications. We have seen in chapter 2 and in the case studies that written documents are decidedly incomplete reservoirs of knowledge that rarely allow replication of past work without the intervention of the original authors, particularly when the work is conducted at a different location and with different material and equipment. Therefore, restricting scientific publication does not support, but actually works against, nonproliferation goals. It also perpetuates the false belief that the fast pace of new scientific developments, aided by a so-called revolution in biotechnology, will eclipse dependence of locally based scientific skills.

Apart from the obvious negative consequence for public health—restricting the spread of scientific data can impede public health authorities' ability to prepare against and respond to a localized outbreak or pandemic—publication restrictions fuel suspicions that the United States is using this data for military purposes. Restricted publications are a common denominator of military programs. For example, during WWII, U.S. physicists working on the Manhattan Project and U.S. bioweapons scientists stopped publishing, and so did Soviet scientists. This apparent lack of transparency can prompt others to pursue bioweapons or to suspect that the United States has a covert offensive bioweapons program.

It is undeniable that the H5N1 controversy and the request of the National Science Advisory Board for Biosecurity (NSABB) to halt publication of the scientific findings have generated a healthy debate about what type of research can yield public health benefits, and under what conditions it is safe to pursue research with potentially dangerous consequences. But in future cases, the NSABB should strive to gain a better understanding of what

would allow replication of scientific work. This implies acquiring a sense of the contingencies associated with various stages of a project; the type of knowledge required to complete these stages; and the extent to which this knowledge is personal, communal, or local.[43] To gain such an understanding, NSABB members need to interview not only the principal investigators, as was the case for the H5N1 experiment, but also the laboratory scientists and technicians who performed the various stages. This may also require a visit to the laboratories involved to inquire about their facilities, equipment, and material. This kind of investigation can better determine the bottlenecks that might prevent replication, what level and combination of expertise might be needed to attempt replication, and to what extent scientific publications reveal any of these essential details.

Two interesting examples of dual-use research of concern can be used as illustrations of how a succinct review of an experiment can yield a false assessment of the threat compared to a more sophisticated analysis: the 2002 poliovirus synthesis and the 2003 creation of the phiX bacteriophage. The poliovirus synthesis was one of the scientific experiments that unleashed a heated debate over the threat posed by scientific publications, because it occurred soon after the events of 2001 and seemed to illustrate how easy it had become to produce dangerous pathogens.[44] The authors at the State University of Stony Brook at New York were indeed able to synthesize the virus by using off-the-shelf materials and data available on the Internet within a three-year period. The following year, the J. Craig Venter Institute (JCVI) in Rockville, Maryland, announced that it had created a bacteriophage—known as phiX 174—using synthetic oligonucleotides within a record two-week period. Taken together, these two experiments seemed to illustrate the fast pace of technological developments and the exponential growth of the proliferation threat.[45]

Yet a more detailed analysis of the two experiments, based on a review of the social, organizational, and managerial factors that characterized them, shows that their achievements were not due to advanced biotechnology but came only after a long-term, painstaking trial-and-error process. These achievements required a combination of skills available at these specific laboratories and the development of scientific protocols that cannot be easily transferred to a new location or adapted to a different agent. In her analysis of the 2002 poliovirus synthesis, Kathleen Vogel found that the team responsible for synthesizing the virus had honed its skills for more than a decade. The same team had synthesized poliovirus in 1991 using a similar method.[46] The knowledge gained from this experience supported the 2002 synthesis work, which itself took three years to achieve. In addition, the success of the experiment hinged on the production of a cell extract needed to grow the virus. Although the method to produce the cell extract is well documented in the scientific literature and seems simple to replicate, the researchers were unsuccessful in using protocols available in the literature.

The laboratory instead used a modified protocol, designed by a researcher who had contributed to the 1991 synthesis. Even with this modified protocol, production of the cell extract was not always successful. To cope with such uncertainties, laboratory personnel adopted a virtually ritualistic approach to their work by using the same equipment, technicians, ingredients, laboratories, and processes in their experiments. Some scientists even had their equipment custom made. Still, failures were frequent.[47] The scientific article that described the experiment was a short two-page overview of the methodology, but it did not discuss the contingencies associated with the experiment, nor the repeated failures that the scientists had to endure.[48]

The JCVI's synthesis of the phiX bacteriophage in 2003 offers similar lessons. Although the synthesis was achieved after what appeared to be only two weeks of effort, the work was truly begun in 1996, by one of the scientists who had been studying the phiX bacteriophage for more than forty years. In 1996, the scientist tried to synthesize the bacteriophage by applying an earlier published method using a polymerase chain reaction (PCR) machine, a technology that has become commonplace in molecular biology. This first attempt failed, and the project was shelved. When work resumed in 2002, the team had expanded to include other world experts in DNA synthesis, including a Nobel laureate, each contributing unique skills. Yet, once again, the team failed. A new protocol had to be developed, requiring extensive experimentation and a review of each step of the experiment. According to the JCVI researchers, one source of the failure was that only about 50 percent of the molecules prepared from an automated DNA synthesizer were of the correct length. In a recent account of the experiment, J. Craig Venter—head of the institute—indicated that DNA synthesizers are prone to error and a simple "'spelling mistake'—the deletion of just one base—out of 1.1 million letters of genetic code meant the difference between life and death, when it came to creating the first synthetic cell."[49] In addition, the researchers indicated that the method they developed for the phiX bacteriophage was not necessarily applicable to other agents—particularly those with a longer genome, such as the smallpox virus. And although the team was ultimately able to synthesize an infectious bacteriophage, some strains of the synthetic phiX DNA had a lower infectivity than that of the natural DNA.[50] Notably, the JCVI work, which included other related research projects, was funded by a Department of Energy grant at the level of $5 million a year over five years.[51] With such characteristics, the likelihood that untrained individuals might replicate the two experiments using the scientific publications are slim to nonexistent. Thus, the full picture behind the synthesis of the phiX bacteriophage in 2003 and the poliovirus synthesis in 2002 question the wisdom of restricting scientific publications in the absence of a clear analysis of the related requirements to achieve reproducibility, including the need for specialized knowledge.

Among bench scientists, the accumulation of knowledge through experimental work and the observation of rigorous disciplines and routines in the laboratory are considered of greater importance to experimental success than the mere acquisition of new technologies. For example, in his memoir, J. Craig Venter stresses the importance of paying attention to details. He credits his early successes in DNA synthesis to rigorous laboratory practices, learned under his mentor at the University of California, San Diego. Whereas other laboratories were unsuccessful using the same technology, he made quick strides due to his acquired ability to make measurements accurately and his practice of checking the purity of reagents used in experimental work, instead of relying on commercial suppliers' claims.[52] This attention to detail and painstaking accumulation of knowledge were also instrumental in Venter's scientific successes that followed the phiX synthesis, culminating in 2010 with the creation of the first self-replicating synthetic bacterial cell. Venter himself emphasized that the work conducted on other projects during the previous fifteen years was essential for his team to solve the new problems presented by the creation of a living cell.[53] Bench scientists also emphasize that one of the most common mistakes postdoctoral fellows make is to let suppliers talk them into using new products or new technologies. Only after wasting time and money with such technologies do they realize that they should have followed the example of their seniors, who emphasize sameness of material and equipment in experimental work.[54] The use of new technologies can also prevent replication of past work, as noted earlier with the example of USAMRIID's unsuccessful attempts to replicate an experiment conducted in 2001.

Current efforts to produce new vaccines and other medical countermeasures (MCM) for biodefense purposes also illustrate the limited role of new technologies in biodefense work compared to skills and expertise. MCM developments have been largely unsuccessful in spite of the involvement of the biotechnology industry, which arguably has access to new technologies. A recent study of biodefense programs has shown that in addition to the well-documented funding and regulatory challenges faced by companies involved in MCM production, there are deeper managerial and organizational problems that are rarely discussed. In fact, current biodefense efforts are plagued with the same managerial issues as past U.S. bioweapons activities: to wit, half a dozen agencies are involved in making programmatic and budget decisions, without much coordination, leading to cost overruns, frequent delays, and some astounding failures.[55] Even worse, work on MCMs at the scientific level seems to have adopted a Soviet-style organization based on the assembly-line model, with various organizations performing different parts of a project without much interaction.[56]

Therefore, new technologies do not, by themselves, allow replication of past work, or transform an untrained individual into a bioterrorist or bioweaponeer overnight. In fact, empirical studies and interviews with bench

scientists indicate that new technologies are not necessarily easy to use, even by trained scientists. They require their users not only to possess prior base knowledge but also to acquire new expertise to solve novel problems created by the use of the technology. Prior base knowledge is necessary because protocols and instructions sold with new bio-equipment often use imprecise language, such as "approximately" or "gently," which require the user to exercise judgment. Such judgment implies relying on prior experience.[57] In an article describing the use of a PCR machine, Michael Lynch shows that although the device aims to automate the amplification of DNA samples—a task that in the past was conducted manually and required time and expertise—PCR users rarely obtain the expected results without difficulty. The kits sold with the machines to facilitate various manipulations actually raise new problems that scientists must solve through extensive experimentation, often with the help of other scientists working inside or outside their institutions.[58] PCR users also note that the automated portion of the work permitted by the machine exists primarily in temperature control; much of the work using a PCR still requires manual skills. And just as interesting, recent studies analyzing various DNA synthesis technologies show that in addition to being prone to errors, different synthesis technologies—including the so-called next-generation sequencing technologies—serve different purposes. Thus, they require their users to determine to what extent one technology or the other will work best for their objectives, which requires the possession of sufficient knowledge to recognize and correct errors. These studies also refer to the various solutions designed by scientists who encountered problems using these technologies, which underscores the importance of having access to a community of experts to solve problems posed by new technologies.[59] Thus, even new-generation technologies require prior expertise and the acquisition of new skills to interpret and troubleshoot problems that are certain to arise.

Finally, new research shows that in the field of gene synthesis—one of the technologies heralded as potentially facilitating the development of bioweapons—skills and laboratory practices remain essential elements of successful outcomes. Although gene synthesis is conducted at the industrial scale, and companies use design software that can be operated by a technician, successful gene design depends on a researcher's experience and the institution's ability to allow learning to emerge over time. Indeed, in spite of the high technological level of the field, there are still technical steps that require manual interventions and skills, particularly during the end stages of the process, where manual manipulation is required (e.g., gene assembly and cloning). These stages are therefore prone to mistakes or unexpected problems, requiring the intervention of an experienced scientist to solve problems.[60]

These examples show that even in the age of the biotechnology revolution, the success of scientific and technical work still primarily depends on

the cumulative and cooperative work of teams of scientists, who acquire specific skills over a lengthy period of time, and who work within local organizational and managerial contexts. Absent the proper expertise and ability to make an expert judgment and learn from experimentation and teamwork, a group or state would not be able to easily replicate past examples or apply the same methods. This finding underscores the importance of assessing more carefully how government organizations go about making decisions concerning what can and cannot be published in scientific journals. It also supports the critical importance of developing a new bioweapons narrative that truly dissuades proliferators from undertaking the stiff challenges that both states and terrorist groups will face in undertaking bioweapons development. Absent the latter development, the Department of Defense's strategy with regard to bioweapons prevention will remain more persuasive than dissuasive.[61]

This is not to say that future technological developments will not expand the boundaries of science, for good or evil. But this does not necessarily mean that the coming advances in biology will make it immensely easier to use biology for harm—or good. Current problems with developing new drugs and therapeutics show why this is the case. A more sophisticated understanding of the role of technology in the future will require us to move from a technocentric focus, which emphasizes what technology can in theory accomplish, to an analysis that takes full account of the interactions between technology, the user, and the materials used. In the bioweapons field, unless future technologies can render biomaterials behavior predictable and controllable,[62] and allow scientists to transition easily from work with one agent to another, the role of expertise and its socio-organizational context will remain critically important barriers to bioweapons development.

Final Thoughts

No one policy will entirely resolve the bioweapons proliferation threat. This book's attention to the variables affecting the sustenance phase of a program, which have remained unappreciated thus far, could be exploited to delay a program's success or perhaps even precipitate its failure. When failure does occur, it is often the product of the program's own doing. Therefore, identifying the program's weaknesses and developing policies designed to exploit and reinforce them can strengthen the barriers to bioweapons. Of course, current policies that affect the formative stage of bioweapons programs and constrain the acquisition of tangible resources should continue, because they can contribute to delaying a program. But a policy exclusively focused on the formative stage of a bioweapons program fails to recognize the unique character of bioweapons development: the barriers to bioweapons are not at the front end of the development process, during procurement,

but further down the line, during processing of fragile microorganisms, which makes the acquisition of expertise a key variable to success.

Extending the argument of this book to other weapons systems may also yield valuable insights to support current and future nuclear, chemical, and missile technology nonproliferation efforts and related threat assessments. Although these weapons systems are based on materials that are more stable than biological agents, and they are more heavily constrained by material procurement than are biological developments, recent studies seem to indicate that nuclear weapons and missile developments are also subject to sociotechnical and organizational constraints that affect knowledge acquisition and, consequently, a program's success.[63] A thorough analysis of the endogenous and exogenous variables that affect specific nuclear and missile programs would therefore provide better assessment of their development timeline and prospects of success. Similar analysis of chemical developments, which remain under-studied, might also prove beneficial.

It would also be important to engage in studies that investigate the loss of technical capacity within the U.S. government to execute its technological oversight responsibilities in order to better assess bioweapons threats. Since the 1970s, the federal government's laboratory system has seen much of its engineering capacity transferred to private industry, leaving these facilities primarily engaged in contract management rather than in research and development activities, which once enabled the government to provide high-quality oversight of contractor performance. This loss of government capacity also includes the wherewithal to assess real from imagined threats, the need for appropriate ways and means to address these threats and develop appropriate countermeasures, not least against bioweapons threats. Military laboratories and private industry often conduct different stages of new biodefense vaccine developments, with little cooperation and integration between government and private industry. Instead, a Soviet-style assembly-line organizational model seems to have settled into their work, which perhaps explains in part the dismal record that private industry has demonstrated thus far in producing effective vaccines. A different social and technical means of organizing biodefense work might prove more successful in producing new medical countermeasures.

Finally, there is the matter of a scientist's responsibility in bioweapons developments. Scientists have sometimes been the instigators of bioweapons programs.[64] In other cases, they have contributed to a program because they feared that their country might be attacked by an enemy; and in still other cases, they were simply forced to contribute by the regime in place.[65] But in a few cases, scientists have been the instigators of atrocities, as was the case for South Africa's Wouter Basson, who reportedly cooperated with South African Death Squads, killing an unknown number of people. In spite of multiple investigations, testimonies, and trials, Basson was acquitted of criminal charges in 2002 and continues to practice as a licensed cardiologist.

Recently, however, the Health Professions Council of South Africa found Basson guilty of "unprofessional conduct," having violated his Hippocratic Oath by heading Project Coast. The council was set to rule on the case in February 2014, but later delayed its decision to an unspecified date.[66] It is possible that the worst that could happen would be for Basson to lose his medical license.[67] This sets a precedent that is far from having any deterrent value whatsoever.

Making contributions to the development and use of a bioweapons program a crime against humanity could serve as a stronger deterrent. Criminalization of bioweapons development at the national level is a requirement under UN Resolution 1540, and several countries have already enacted legislation making it a crime for terrorists to develop, use, or acquire mass destruction weapons, including biological weapons.[68] Article IV of the BWC also requires member states to issue the necessary legislation to implement the treaty at the national level, which is an implicit criminalization requirement. However, both the BWC and UN Resolution 1540 suffer from insufficient implementation. For example, the content of the legislation reported by individual countries to the UN Resolution 1540 Committee is unequal, as is enforcement of the legislation at the national level. Yet 1540 Committee personnel do not have the mandate to evaluate this legislation or issue a template of what constitutes exemplary legislation. Elevating the offense to a crime against humanity would create a level playing field, placing all potential violators under the same international penalty. The issue has been under discussion for a few years within the International Criminal Court (ICC), but disagreements between members about whether discussions about the criminalization of biological and chemical weapons use should be tied to nuclear weapons use have prevented the explicit inclusion of biological weapons in the Rome Statute, the ICC's founding document.[69] It is high time to reenergize this discussion in order to deter scientists from becoming bioweapons scientists.

APPENDIX 1

American Bioweapons Program

Contractors

No.	University/College Name (alphabetical order)	# of Contracts; Contract Dates Beginning/End*
1.	U. of Arizona	2; 1961/70
2.	U. of Arkansas	3; 1954/57
3.	Baylor College of Medicine	1; 1966/72
4.	Brooklyn College	1; 1960/61
5.	Bucknell University	2; 1952/54
6.	U. of California	12; 1950/68
7.	U. of Chicago	13; 1950/66
8.	U. of Cincinnati	5; 1950/56
9.	Columbia University	1; 1952/54
10.	Cornell University	2; 1951/55
11.	Duke University	5; 1951/68
12.	Emory University	1; 1954/57
13.	U. of Florida	6; 1952/70
14.	Florida State University	3; 1951/56
15.	Fordham University	2; 1965/67
16.	George Washington University	2; 1952/59
17.	Hahn E. Mann Med. College & Hospital	2; 1953/56
18.	Harvard College	5; 1949/68
19.	U. of Hawaii	2; 1967/70
20.	U. of Illinois	7; 1950/68
21.	U. of Indiana	4; 1951/66
22.	Iowa State College of Agriculture	6; 1949/56
23.	John Hopkins University	12; 1950/71
24.	Kansas State Univ. of Agriculture & Applied Science	5; 1956/63
25.	U. of Kansas	4; 1949/54
26.	Lehigh University	1; 1953
27.	Marquette School of Medicine	1; 1969/70
28.	U. of Maryland	8; 1951/69
29.	U. of Massachusetts	1; 1954/55
30.	U. of Miami	1; 1969/70
31.	Michigan State College	5; 1950/56
32.	Michigan State University	3; 1956/68
33.	U. of Michigan	7; 1951/69

(continued)

(continued)

No.	University/College Name (alphabetical order)	# of Contracts; Contract Dates Beginning/End*
34.	U. of Minnesota	18; 1950/70
35.	Mississippi State College	2; 1951/55
36.	U. of Mississippi	3; 1951/55
37.	U. of Missouri	1; 1950/52
38.	Montana State University	1; 1967/70
39.	U. of Nebraska	2; 1948/54
40.	New Mexico College of Agriculture & Mechanic Arts	1; 1960/62
41.	New Mexico State University	1; 1964/68
42.	New York University	2; 1951/56
43.	State University of New York Research Foundation	3; 1952/69
44.	State University of North Carolina	2; 1963/64
45.	U. of North Carolina	1; 1951/54
46.	North Dakota Agricultural College	2; 1960/61
47.	Northwestern Univ.	7; 1950/65
48.	U. of Notre Dame	1; 1951/54
49.	Ohio State University Research Foundation	8; 1952/69
50.	Ohio University	2; 1955/58
51.	Oklahoma Agricultural and Mechanical College	1; 1951/53
52.	Oklahoma State University	2; 1963/69
53.	Oregon State University	2; 1964/70
54.	Pennsylvania State College	3; 1951/71
55.	U. of Pennsylvania	4; 1955/67
56.	U. of Pittsburgh	1; 1951/53
57.	Princeton University	1; 1967/69
58.	U. of Puerto Rico	1; 1952
59.	Purdue Research Foundation	6; 1952/70
60.	Rhode Island State College	1; 1951/52
61.	U. of Rhode Island	1; 1953/55
62.	Rutgers College	1; 1950/51
63.	Rutgers University	3; 1951/63
64.	U. of Southern California	3; 1952/57
65.	Stanford Research Institute	3; 1954/66
66.	Stanford University	4; 1951/59
67.	Syracuse University	2; 1967/70
68.	U. of Tennessee	2; 1951/65
69.	Texas Agricultural & Mechanical College	5; 1953/70
70.	U. of Texas	8; 1951/70
71.	U. of Utah	6; 1951/59
72.	U. of Virginia	2; 1965/69
73.	Washington State University	4; 1959/70
74.	Wesleyan University	2; 1951/55
75.	West Virginia University	14; 1949/66
76.	Western Reserve University	3; 1951/53
77.	U. of Wisconsin	21; 1950/69
78.	Yale University	2; 1963/67

No.	Company Name (alphabetical order)	# of Contracts; Contract Dates Beginning/End
1.	AAI Corp.	2; 1966/68
2.	Aerojet-General Corp	29; 1956/70
3.	Aeroprojects, Inc.	9; 1950/70
4.	Aerotec Corp.	1; 1955/56
5.	Agricultural Aviation Engineering Corp.	1; 1963
6.	Agricultural Specialty Co.	1; 1963/65
7.	Aircraft Armaments, Inc.	4; 1951/65
8.	AiResearch Mfg. Corp.	2; 1964/67
9.	Allied Chemical Corp.	3; 1958/68
10.	Allied Helicopter Service, Inc.	1; 1967
11.	Allied Research Associates, Inc.	1; 1957/58
12.	Amchem Products, Inc.	1; 1959/61
13.	American Cyanamid Co.	2; 1957/65
14.	American Institute of Crop Ecology	2; 1955/65
15.	American Standard, Inc.	2; 1965/67
16.	American Type Culture Collection, Inc.	2; 1952/67
17.	Anstice Co., Inc.	1; 1951
18.	Ansul Chemical Co.	2; 1962/69
19.	Applied Science Laboratories, Inc.	1; 1961/62
20.	Armour Research Foundation of IIT	5; 1951/56
21.	Arthur D. Little, Inc.	4; 1950/55
22.	Associated Nucleonics, Inc.	3; 1960/62
23.	Atlas Powder Co.	1; (typo in original document; contract end date precedes start date)
24.	Auburn Research Fdn.	1; 1953/57
25.	AVCO Corp.	5; 1959/70
26.	Baltimore Biological Laboratory	1; 1963/66
27.	Battelle Memorial Institute	11; 1952/65
28.	Beckman Instruments, Inc.	3; 1966/70
29.	Ben Venue Labs, Inc.	2; 1953/55
30.	Bendix Corp.	2; 1962/65
31.	Bete Fog Nozzle, Inc.	1; 1951/52
32.	Bioferm, Inc.	3; 1962/63
33.	Bionetics Research Laboratories	2; 1966/68
34.	Biosearch Co.	1; 1962/63
35.	Bio-Search and Development Co.	1; 1962/63
36.	Bjorksten Research Laboratories	1; 1964/65
37.	Black Mfg. Co.	1; 1951/52
38.	Booz-Allen Applied Research, Inc.	5; 1957/68
39.	Boyce-Thompson Inst.	3; 1963/69
40.	Buffalo Electro-Chemical Co., Inc.	1; 1951
41.	California (State of)	2; 1951/53
42.	Cambridge Technology, Inc.	2; 1967/68
43.	CEIR, Inc.	1; 1958/59
44.	Commercial Solvents Corp.	1; 1963/65
45.	Continental Oil Co.	1; 1962/64
46.	Control Data Corp (fmr. CEIR Corp.)	2; 1964/70
47.	Cordis Corp.	1; 1964/65
48.	Cornell Aeronautical Lab, Inc.	1; 1960/62
49.	Cyclo Chemical Corp.	2; 1964/70
50.	Daniel, Mann, Johnson & Mendenhall	1; 1967/68
51.	Danielson Mfg. Co.	1; 1953/68

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No.	Company Name (alphabetical order)	# of Contracts; Contract Dates Beginning/End
52.	Day & Zimmerman	1; 1955
53.	DeBell & Richardson, Inc.	1; 1955/57
54.	Dorr-Oliver, Inc.	1; 1962/64
55.	Doughnut Corp of America	1; 1952/53
56.	Dow Chemical Co.	5; 1958/70
57.	Dry-Freeze Corp.	2; 1951/52
58.	A.B. DuMont Labs, Inc.	2; 1953/56
59.	Edo Corp.	1; 1964/65
60.	Environmental Research Corp.	2; 1967/71
61.	Ethyl Corp.	1; 1962/66
62.	Everedy Co.	1; 1951/52
63.	Fairchild Engine & Airplane Co.	1; 1959/60
64.	Fairchild Stratos Corp.	4; 1960/64
65.	Falcon Plastics	1; 1958/59
66.	Farrand Optical Co.	2; 1956/58
67.	Fawn Plastics Co., Inc.	1; 1961/62
68.	Fletcher Enamel Co.	1; 1950/51
69.	FMC Corp.	4; 1964/70
70.	Fostoria Presses Steel Corp.	1; (typo in original document; contract end date precedes start date)
71.	Foundation for Research on the Nervous System	2; 1963/69
72.	Franklin Electronics, Inc.	1; 1966
73.	Franklin Inst.	2; 1968/70
74.	Gelman Instrument Co.	1; 1964/69
75.	General American Transportation Co.	2; 1961/66
76.	General Aniline & Film Co.	1; 1963/64
77.	General Dynamics Corp.	1; 1955/56
78.	General Electric Co.	5; 1960/67
79.	General Mills, Inc.	7; 1950/57
80.	Georgia Tech Research Inst.	5; 1950/57
81.	B.F. Goodrich Co.	2; 1953/56
82.	Grinnell Co., Inc.	1; 1954/58
83.	Henry Ford Hospital	2; 1951/53
84.	Hills-McCanna Co.	1; 1957/58
85.	Holmes & Narver, Inc.	1; 1968/69
86.	Honeywell Regulator, Co.	5; 1955/62
87.	Hooker Chemical Corp.	1; 1964/65
88.	Hyland Labs, Inc.	1; 1964/66
89.	IIT Research Inst.	10; 1955/70
90.	Industrial Corp.	1; 1962/63
91.	Insect Control & Research, Inc.	3; 1960/66
92.	International Business Machines	1; 1968/69
93.	International Minerals and Chemicals Corp.	2; 1964/68
94.	S.C. Johnson & Son, Inc.	1; 1960/62
95.	D. Kennedy Co.	1; 1959/60
96.	Kent Mfg. Co.	1; 1950/51
97.	Kentucky Research Fdn.	1; 1954/56
98.	W. Kidde & Co., Inc.	1; 1955/58
99.	Knapp-Monarch Co.	1; 1952/53
100.	Kuljian Corp.	1; 1954/56
101.	Lambert Pharmaceutical Co.	1; 1950/51

No.	Company Name (alphabetical order)	# of Contracts; Contract Dates Beginning/End
102.	Litton Systems, Inc.	14; 1960/68
103.	Lockheed Aircraft Co.	3; 1965/69
104.	Long Island Biological Association	6; 1950/55
105.	Lovell Chemical Co.	3; 1950/54
106.	Lux Clock Mfg. Co.	1; 1953
107.	Machine & Tool Design Co.	1; 1954
108.	Magna Corp.	1; 1962/63
109.	G.L. Martin Corp.	1; 1950
110.	Martin Marietta Corp.	1; 1953/55
111.	Mathieson Chemical Corp.	2; 1952/54
112.	Maxon Electronics Corp.	1; 1961/63
113.	MB Associates	5; 1964/69
114.	D.M. McBean, Inc.	1; 1953/57
115.	McDonnell-Douglas Corp.	1; 1960/65
116.	Mellon Inst. of Industrial Research	4; 1950/55
117.	Merck & Co., Inc.	2; 1955/61
118.	Metal Matic, Inc.	1; 1954
119.	Meteorology Research, Inc.	1; 1965/67
120.	Metronics Associates, Inc.	2; 1966/70
121.	Michigan (State Dept. of Health)	1; 1965/67
122.	Midwest Research Inst.	4; 1961/71
123.	Millipore Filter Corp.	1; 1954/55
124.	Mine Safety Appliances Co.	5; 1955/64
125.	Minneapolis-Honeywell Regulator Co.	3; 1952/56
126.	Molded-Resin Fiber Co.	1; 1951/53
127.	Monomer-Polymer Co.	1; 1951/52
128.	Monsanto Research Corp.	4; 1963/69
129.	MTD Research & Development	1; 1960/61
130.	Nation Research Corp.	1; 1961
131.	National Academy of Sciences	1; 1957/62
132.	Nation Research Corp.	1; 1961
133.	North American Aviation, Inc.	2; 1957/62
134.	Northrop Corp.	1; 1966/67
135.	G.O. Noville & Associates, Inc.	1; 1953/57
136.	Okanagan Copter Sprays, Ltd.	1; 1967
137.	Olin Mathieson Chemical Corp.	2; 1955/58
138.	Optics Technology, Inc.	2; 1963/66
139.	Ordnance Engineering Corp.	1; 1955/56
140.	T.G. Owe Berg, Inc.	1; 1966/67
141.	Park Thompson	1; 1950/51
142.	Parke, Davis & Co.	7; 1951/58
143.	R.M. Parsons Co.	10; 1951/63
144.	Pennsalt Chemical Corp.	3; 1962/70
145.	Pfizer, Charles & Co., Inc.	3; 1963/67
146.	Philco Corp.	1; 1961/64
147.	Photomechanisms, Inc.	2; 1958/62
148.	Planning Research Corp.	1; 1960/61
149.	Plax Corp.	1; 1952
150.	Pneumo-Dynamics Corp.	1; 1963/64
151.	Polaroid Corp.	6; 1951/60
152.	Prengle, Duckler & Crump	1; 1961/64
153.	Prime, Inc.	3; 1950/55
154.	Rheem Mfg. Co.	1; 1952/54

(continued)

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No.	*Company Name (alphabetical order)*	*# of Contracts; Contract Dates Beginning/End*
155.	Ryan Aeronautical Co.	1; 1963
156.	Sharpley Laboratories, Inc.	1; 1963/66
157.	Shell Chemical Corp.	1; 1958/59
158.	Sierra Engineering Co.	1; 1964/65
159.	Smithsonian Institution	4; 1951/69
160.	Southern Research Inst.	16; 1951/63
161.	Southwest Research Inst.	1; 1957
162.	Specialized Instruments Corp.	2; 1952/54
163.	Sperry Piedmont Co.	1; 1965
164.	Sperry Utah Co.	2; 1963/65
165.	Spraying Sya Corp.	1; 1951/52
166.	Squibb, E.R. & Sons	1; 1952/53
167.	Taller Y. Cooper, Inc.	1; 1955/57
168.	Texas Rice Improvement Assoc.	1; 1958
169.	Thompson Helicopters, Inc.	1; 1964
170.	Townsend Engineered Products, Inc.	1; (typo in original document; contract end date precedes start date)
171.	Tracerlab, Inc.	6; 1949/58
172.	Traveler's Research Corp.	1; 1966/68
173.	Trident Engineering Associates, Inc.	1; 1965
174.	Trio Chemical Works, Inc.	4; 1967/69
175.	Trudeau, Edward L. Foundation	1; 1952/53
176.	U.S. Industrial Corp.	1; 1965
177.	U.S. Rubber Co.	1; 1964/65
178.	U.S. Steel Co.	1; 1958/59
179.	Universal Match Corp.	3; 1954/57
180.	Vitro Engineering Co.	1; 1961/62
181.	Wahl-Henius Inst.	2; 1952/54
182.	Warner-Lambert Pharm. Co.	1; 1953/55
183.	Wiegand, Edwin L. Co.	1; 1955/56
184.	Wistar Inst. of Anatomy	3; 1960/68
185.	Worchester Fdn. for Experimental Biology	1; 1962/63
186.	Yoh, H.L. & Co., Inc.	2; 1955/56

Source: U.S. Army, *U.S. Army Activity in the U.S. Biological Warfare Programs*, vol. 1 (Washington, DC: Government Printing Office, 1977), 80–100, http://www.gwu.edu/~nsarchiv/NSAEBB/NSAEBB58/RNCBW_USABWP.pdf.

* Entries that have only one date indicate contracts that started and ended the same year.

APPENDIX 2

American Bioweapons Program

Approximate Budget Figures

Most sources provide an overall budget for both the chemical and biological weapons programs. The budget figures in this table relate to the bioweapons program only and have been gleaned from a variety of published articles, as well as unpublished archival data located at the American Society for Microbiology in Baltimore, Maryland. Among these, some sources provide partial budget data, related to research and development (R&D), procurement of equipment, or facility construction at Fort Detrick and satellite bioweapons sites. A small number of sources, however, provide budget data for a specific period of time, along with a breakdown in spending. When available, these latter sources have been included in the following table, whereas the partial data for that same period are not included, to avoid double counting. Finally, there is no data available for 1948, 1957, and 1967.

Year	*Budget*	*Item*	*Source*
1942–45	**$60m**	**Total wartime budget**	**[1], 116**
	Including:		
	$685K for research (July '42–July '43)	Funding made available to the War Research Service (WRS) from President's Emergency Funds to support research at 28 universities	**[2], 135**
		This amount probably includes the WRS initial funding of $200K in 1942	**[1], 117**
	About $13m	Total construction cost of Camp Detrick research and testing facilities	**[2], 143**
	About $1m	For research contracts in September between 1944 and March 1945	**[2], 145**

(continued)

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Year	*Budget*	*Item*	*Source*
1946	**$3.9m**	R&D and facility maintenance	**[2], 144**
1947	**$2.7m**	Total budget	**[3], 26**
			[2], 554
1949	**$4.7m**	R&D and facility maintenance	**[4], 9**
1950	**$5.9m**	R&D and facility maintenance	**[4], 9**
			[12], 48[a]
1951–53	**$350m**		**[12], 48**
	Including:		
	$58.5m	**R&D**	
	$156.1m	**Construction**	
	$56.3m	Construction of R&D laboratories (In 1953 alone, $10m was invested in laboratory construction at Fort Detrick.)[b]	
	$12.8m	Construction of testing facilities	
	$87m	Construction of Pine Bluff production plant^^	
	$131.1m	**Production and Procurement**	
	(Operating costs not included: maintenance and salaries)		
1954	**$25.4m**[c]	Overall bioweapons budget	**[10], 202**
1954–58	**$15.6m**	Laboratory construction	**[7], 40**
1958	**$10m**	R&D and warhead/munitions development	**[6], 7–9**
1959	**$20m**	R&D at Fort Detrick	**[11], 271**
	$200k	Anticrop research reactivated at Fort Detrick	**[10], 207**
1962	**$20.1m**	Budget for the expansion of Pine Bluff production plant	**[7], 47**
1963	**$42m**[d]	R&D at Fort Detrick (Army: $40m; USAF: $2m)	**[5], 2**
1966	**$38m**	Total bioweapons funding (Army)	**[7], 51**
1968	**$31.55m**		**[8], 1**
	Including:		
	$26.9m	R&D, and test and evaluation	
	$ 2.1m	Procurement, equipment, and missiles (Army)	
	$ 0.65m	Operations and maintenance (Army)	
	$ 1.9m	U.S. Air Force, U.S. Navy, and NASA	
1969	**$31m**[e]	Total bioweapons funding (Army)	**[9], 59**
			[7], 51
			[11], 271

[a] Endicott and Hagerman provide a budget of $5.3m for 1950.

[b] See also [7], 37.

[c] Alastair Hay indicates that $20m was authorized for construction at Fort Detrick in 1953. It is not clear, however, whether the 1954 budget he lists includes this amount. Hay also indicates, "In fiscal [year] 1953, the lack of facilities limited work on anti-animal agents." It is possible that the funds were authorized but allocated late in 1954 ([10], 201). Army reports indicate that $15.6 million was allocated for construction at Fort Detrick between 1954 and 1958 ([7], 40).

[d] Jeffrey K. Smart provides a budget of $38m in 1963 ([9], 51–52).

[e] SIPRI provides a slightly lower budget for 1969: $29.4m for R&D and procurement at Fort Detrick ([11], 271).

Note: Source [5] indicates that about $300m was spent on bioweapons R&D between 1943 and 1963. It is likely that this amount includes equipment procurement and facility construction as well as R&D work. The document consists of captions from a slide presentation, listing the equipment and new facilities built at Fort Detrick during this period. The caption "About 300 million spent to date on BW R&D" comes at the bottom of the equipment/facility construction list. (See [5], 2).

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Notes

Chapter 1

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Chapter 3

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73. Examples of irreproducibility because of location are provided in Kathleen M. Vogel, *Phantom Menace or Looming Danger? A New Framework for Assessing Bioweapons Threats* (Baltimore: Johns Hopkins University Press, 2013), chap. 3; Gormley, *Missile Contagion*, 89–91; Galison, *Image and Logic*, chap. 3. For an example of the role of the environment when conducting an experiment, see Hoddeson, Henriksen, Meade, and Westfall, *Critical Assembly*, 3.

74. Victor E. Volchkov, Valentina A. Volchkova, Elke Muhlberger, Larissa V. Kolesnikova, Michael Weik, Olga Dolnik, and Han-Dieter Klenk, "Recovery of Infectious Ebola Virus from Complementary DNA: RNA Editing of the GP Gene and Viral Cytoxicity," *Science*, vol. 291 (March 9, 2001): 1965–69.

75. Ibid., 1965.

76. Interviews with anonymous scientist, September 13, 2012, and September 26, 2012.

77. Interview with former Fort Detrick laboratory technician Richard Delauter, Frederick, MD, August 12, 2008.

78. Sally Smith Hughes, *Genentech: The Beginnings of Biotech* (Chicago: University of Chicago Press, 2011), 126.

79. Alexander Montgomery, "Stop Helping Me: When Nuclear Assistance Impedes Nuclear Programs," in Adam Stulberg and Matt Fuhrmann (eds.), *Nuclear Renaissance and International Security* (Stanford, CA: Stanford University Press, 2013), 177–202; Jacques Hymans, *Achieving Nuclear Ambitions: Scientists, Politicians, and Proliferation* (Cambridge: Cambridge University Press, 2012).

80. There are exceptions in less complex weapons programs than nuclear or biological weapons development. South Korea's cruise missile program is probably almost entirely endogenous. See Gormley, *Missile Contagion*, 55, 105–6. Evidence of foreign assistance in various WMD programs can also be found in Jeffrey T. Richelson, *Spying on the Bomb: American Nuclear Intelligence from Nazi Germany to Iran and North Korea* (New York: W.W. Norton & Company, 2006); Matthew Kroenig, *Exporting the Bomb: Technology and the Spread of Nuclear Weapons* (Ithaca, NY: Cornell University Press, 2010); Jonathan Tucker, *War of Nerves: Chemical Warfare from World War I to Al-Qaeda* (New York: Anchor Books/Random House, 2007).

81. Jeanne Guillemin, *Biological Weapons: From the Invention of State-Sponsored Programs to Contemporary Bioterrorism* (New York: Columbia University Press, 2005); Ed Regis, *The Biology of Doom: The History of America's Secret Germ and Warfare Project* (New York: Henry Holt and Company, 1999).

82. Interviews with former U.S. biological weapons scientists, between 2008 and 2010.

83. Norman Covert, *Cutting Edge: The History of Fort Detrick*, chap. 6.

84. Lieutenant Colonel Arvo T. Thompson, "Report on Japanese Biological Warfare (BW) Activities," Army Service Forces, Camp Detrick, MD, May 31, 1946, ASM Archives.

85. Interviews with former Soviet bioweapons scientists, between 2006 and 2011. See also Ken Alibek with Stephen Handelman, *Biohazard* (New York: Random House, 1999).

86. Ken Alibek, "Behind the Mask: Biological Warfare," *Perspective*, vol. 9, no. 1 (September–October 1998), http://www.bu.edu/iscip/vol9/Alibek.html.

87. Sheldon Harris, "Japanese Biological Warfare Experiments and Other Atrocities in Mandchuria, 1932–1945, and the Subsequent United States Cover Up: A Preliminary Assessment," *Crime, Law and Social Change*, vol. 15, no. 3 (1991): 171–99.

88. Donald MacKenzie and Graham Spinardi, "Tacit Knowledge, Weapons Design, and the Uninvention of Nuclear Weapons," *American Journal of Sociology*, vol. 101, no. 1 (1995): 44–99.

89. Collins and Frantz, *Fallout*, 41.

90. Fitzpatrick, *Nuclear Black Markets*, 77–79; Joby Warrick and Peter Slevin, "Libyan Arms Designs Traced Back to China," *Washington Post*, February 15, 2004, A1, http://www.washingtonpost.com/wp-dyn/articles/A42692-2004Feb14_2.html; "Libyan Nuclear Weapons," *Global Security Newswire*, http://www.globalsecurity.org/wmd/world/libya/nuclear.htm.

91. Mahdi Obeidi and Kurt Pitzer, *The Bomb in My Garden: The Secrets of Saddam's Nuclear Mastermind* (Hoboken: Wiley, 2004), chaps. 3–7. The Iraqis were also unsuccessful with a prior attempt at implementing the less sophisticated electromagnetic isotope enrichment process (EMIS), based on documentation declassified by the United States after WWII. The machines that they produced endogenously, with some foreign procurement, were inefficient and encountered many problems. They were also labor intensive, while Iraq lacked the skilled personnel to run them. See Robert E. Kelley, "The Iraqi and South African Nuclear Weapon Programs: The Importance of Management," *Security Dialogue*, vol. 27, no. 1 (1996): 34.

92. Obeidi and Pitzer, 120–23; Hymans, *Achieving Nuclear Ambitions*, chap. 3.

93. Kelley, "The Iraqi and South African Nuclear Weapon Programs, 32. See also Hymans, *Achieving Nuclear Ambitions*, chap. 3; Obeidi and Pitzer, *The Bomb in My Garden*, chap. 4.

94. It is worth noting that Iraq's procurement and training efforts received very little scrutiny. The Australia group was created in 1984, and it started controlling bioweapons related material and equipment only in the early 1990s. For a list of Iraq's suppliers, see "Foreign Suppliers to Iraq's Biological Weapons Program," James Martin Center for Nonproliferation Studies, http://cns.miis.edu/wmdme/flow/iraq/; see also "Iraq Biological Chronology," Nuclear Threat Initiative, http://www.nti.org/media/pdfs/iraq_biological_1.pdf?_=1316466791.

Chapter 4

1. On the former U.S. program, see Jonathan Tucker, "A Farewell to Germs: The U.S. Renunciation of Biological and Toxin Warfare, 1969–70," *International Security*, vol. 27, no. 1 (Summer 2002): 107–48; Barton Bernstein, "Origins of the U.S. Biological Warfare Program," in Susan

Wright (ed.), *Preventing a Biological Arms Race* (Cambridge, MA: MIT Press, 1991), 9–25; Susan Wright, "Evolution of the Biological Warfare Policy: 1945–1990," in Wright (ed.), *Preventing a Biological Arms Race*, 26–68; John Ellis Van Courtland Moon, "The US Biological Weapons Program," in Mark Wheelis, Lajos Rozsa and Malcom Dando (eds.), *Deadly Cultures: Biological Weapons since 1945* (Cambridge, MA: Harvard University Press, 2006), 9–46; Jeanne Guillemin, *Biological Weapons: From the Invention of State-Sponsored Programs to Contemporary Bioterrorism* (New York: Columbia University Press, 2005); Milton Leitenberg, "Biological Weapons in the Twentieth Century: A Review and Analysis," *Critical Reviews in Microbiology*, vol. 27, no. 4 (2001): 267–320; Barton J. Bernstein, "America's Biological Warfare Program in the Second World War," *Journal of Strategic Studies*, vol. 11, no. 3 (September 1988): 292–317; Alastair Hay, "Simulants, Stimulants and Diseases: The Evolution of the United States Biological Warfare Programme, 1945–60," *Medicine, Conflict and Survival*, vol. 15, no. 3 (1999): 198–214; Edward Regis, *The Biology of Doom: The History of America's Secret Germ Warfare Project* (New York: Henry Holt, 1999).

2. The concept of heterogeneous engineer was discussed in chapter 3.

3. Barton Bernstein, "The Birth of the U.S. Biological-Warfare Program," *Scientific American*, vol. 256, no. 6 (June 1987): 116–21.

4. Richard M. Clendenin, "Science and Technology at Fort Detrick, 1943–1968," Frederick, MD, 1968, 3, 19 (American Society for Microbiology Archives, University of Maryland Baltimore County, Catonsville, MD, 21228, File: "Regional History, Maryland").

5. Bernstein, "The Birth of the U.S. Biological-Warfare Program," 116.

6. Leo P. Brophy, Wyndham D. Miles, and Rexmond C. Cochrane, *The Chemical Warfare Service: From Laboratory to Field* (Washington, DC: Center of Military History, U.S. Army, 1988), 108; U.S. Army, *U.S. Army Activity in the U.S. Biological Warfare Programs*, vol. 1 (Washington, DC: Government Printing Office, 1977), http://www.gwu.edu/~nsarchiv/NSAEBB/NSAEBB58/RNCBW_USABWP.pdf.

7. U.S. Army, "United States Army Dugway Proving Ground," http://www.dugway.army.mil/History.aspx.

8. "Interview—Mr. William Patrick," *Homeland Defense Journal*, October 27, 2000.

9. Ibid.; U.S. Army, *U.S. Army Activity in the U.S. Biological Warfare Programs*, 77; George W. Christopher, Theodore J. Cieslak, Julie A. Pavlin, and Edward M. Eitzen Jr., "Biological Warfare: A Historical Perspective," *Journal of the American Medical Association*, vol. 278, no. 5 (August 6, 1997): 412–17; James W. Martin, George W. Christopher, and Edward M. Eitzen Jr., "History of Biological Weapons: From Poisoned Darts to Intentional Epidemics," in Zygmunt F. Dembek (ed.), *Medical Aspects of Biological Warfare* (Washington DC: Borden Institute, 2007), https://ke.army.mil/bordeninstitute/published_volumes/biological_warfare/BW-ch01.pdf.

10. The list of technical reports was obtained by Muckrock.com in June 2013 under a FOIA request. Although the technical reports are not available for public consultation, the list provides an overview of the type of work conducted and can be accessed at: https://www.muckrock.com/foi/united-states-of-america-10/dugway-proving-ground-technical-reports-4890/#713163-morisy-foia-fa-13-0036-dpg_1964.

11. Charles W. Riggs, "Estimates of Decay of Aerosolized Dried Psittacosis and Variola Virus Preparations in the 1500-Liter Toroid," Report Number: ANALYSIS-5136, CBRNIAC Number: CB-123372, November 14, 1961; Joseph V. Jemski, "Assessment of Aerosols of Dried Variola Virus Preparations," Report Number: TEST-A-1571 62-TE-1571, CBRNIAC Number: CB-127132, March 20, 1963; Joseph V. Jemski, "Assessment of Aerosols of Dried Variola Virus Preparations," Report Number: TEST-A-1555 61-TE-1555, CBRNIAC Number: CB-127135, March 20, 1963 (all available on Muckrock.com).

12. Joseph V. Jemski, "Estimation of the Aerosol Parameters of Variola Virus (Yamada Strain) When Disseminated by the Complete E25 at 72F and 50 percent Relative Humidity," Report Number: TEST-A-1336, CBRNIAC Number: CB-125866, January 5, 1962; Ellis J. Tonik, and Joseph V. Jemski, "An Estimation of the Aerosol Parameters of UL Disseminated by the E25 Item at 72F and Relative Humidities of 50 and 85 percent," Report Number: TEST-A-1429, CBRNIAC Number: CB-125865, May 21, 1962 (all available on Muckrock.com).

13. U.S. Army, *U.S. Army Activity in the U.S. Biological Warfare Programs*, 77–78.

14. See, for example, Scott Shane, "Burried Secrets of Biowarfare," *Baltimore Sun*, August 1, 2004, 1A; Norman M. Covert, *Cutting Edge: The History of Fort Detrick* (Fort Detrick: Public Affairs Office, 1997), chaps. 4 and 6, http://www.detrick.army.mil/cutting_edge/.

15. Covert, *Cutting Edge*; "Selected Contributions of the Biological Laboratories at Fort Detrick to Science and the Public Welfare, 1943–1970" (ASM Archives, University of Maryland Baltimore County, Catonsville, MD, 21228, File: "Regional History, Maryland").

16. Manuel Barbeito, former Fort Detrick Safety Section chief, presentation at "Panel Discussion with Former U.S. Bioweapons Scientists," George Mason University, Fairfax, VA, March 17, 2009; see also U.S. Army, *U.S. Army Activity in the U.S. Biological Warfare Programs*; and "Selected Contributions of the Biological Laboratories at Fort Detrick to Science and the Public Welfare."

17. For more information on testing activities, see Leonard A. Cole, *The Army's Germ Warfare Tests over Populated Areas* (Lanham, MD: Rowman and Littlefield, 1988); Senate Committee on Armed Services, *The Department of Defense's Inquiry into Project 112/Shipboard Hazard and Defense (SHAD) Tests: Hearing Before the Subcommittee on Personnel of the Committee on Armed Services, 107th Congress, Second Session, October 10, 2002*, S. hrg. 107–810 (Washington, DC: U.S. GPO: 2003): 1–39; "Project 112/SHAD: Shipboard Hazard and Defense," Medical Countermeasures, http://mcm.dhhq.health.mil/cb_exposures/project112_shad/shad.aspx.

18. U.S. Army, *U.S. Army Activity in the U.S. Biological Warfare Programs*; "Interview—Mr. William Patrick."

19. Ibid. See also Robert L. Mole and Dale M. Mole, *For God and Country: Operation Whitecoat, 1954–1973* (Brushton, NY: Teach Service, 1998).

20. Ira L. Baldwin, *My Half Century at the University of Wisconsin* (Madison, WI: Omnipress, 1995), 118–20; Interview with former Fort Detrick pilot plant shift supervisor, Frederick, Maryland, March 22, 2008.

21. The development of a large-scale production method for penicillin is usually credited to the pharmaceutical company Pfizer, because it was the first company to open a commercial large-scale production plant for penicillin in 1944. However, the development of the process allowing the mass production of penicillin was the result of the collaboration of several university, private, and government laboratories working under the auspices of the U.S. War Production Board. A key discovery allowing the mass production of penicillin is due to Dr. Coghill (Department of Agriculture laboratory, Peoria, Illinois), who designed a culture media based on corn steep liquor, which dramatically increased the yield of penicillin. In his memoir, Ira Baldwin indicated that Coghill collaborated with the University of Wisconsin, which was then engaged in developing deep-tank fermentation methods for penicillin. Other laboratories and pharmaceutical companies contributed solutions to several other problems of large-scale production, including excess foaming issues in the fermentation liquid, the extraction of penicillin through freeze-drying under vacuum, and the identification of the strains that would produce greater amounts of penicillin. This collaborative work allowed the development of a process that yielded sufficient amounts of penicillin to meet war needs, but the mass production of penicillin still faced many scientific challenges, which pharmaceutical companies, universities, and government laboratories continued to investigate after the war. For example, at Fort Detrick, Riley Housewright and others studied penicillin resistance, contamination problems, and purification methods of penicillin, and published their results in several scientific papers. See Margaret Goldsmith, *The Road to Penicillin: A History of Chemotherapy* (London: Lindsay Drummond, 1946); Gladys L. Hobby, *Penicillin: Meeting the* Challenge (New Haven: Yale University Press, 1985); "Discovery and Development of Penicillin," American Chemical Society, http://www.acs.org/content/acs/en/education/whatischemistry/landmarks/flemingpenicillin.html#P40_7383; "Penicillin," *Science*, vol. 98, no. 2539 (August 27, 1943): 192; Riley D. Housewright and Richard J. Henry, "Studies on Penicillinase: I. The Production, Partial Purification, and Practical Application of Penicillinase," *Journal of Biological Chemistry*, vol. 167 (1947): 553–57; Baldwin, "My Half Century at the University of Wisconsin," 118–20; Riley D. Housewright and Richard J. Henry, "Studies on Penicillinase: II. Manometric Method of Assaying Penicillinase and Penicillin, Kinetics of the Penicillin-Penicillinase Reaction, and the Effects of Inhibitors on Penicillinase," *Journal of Biological Chemistry*, vol. 167, no. 2 (1947): 559–71; Riley D. Housewright and Richard J. Henry,

"Studies on Penicillinase: III. The Effect of Antipenicillinase on Penicillin-Resistant Organisms," *Journal of Bacteriology*, vol. 53, no. 2 (1947): 241–47; Andrew J. Moyer and Robert D. Coghill, "Penicillin: The Laboratory Scale Production of Penicillin in Submerged Cultures by Penicillium Notatum Westling (NRRL 832), *Journal of Bacteriology*, vol. 51, no. 1 (1946): 79–93.

22. "Selected Contributions of the Biological Laboratories at Fort Detrick to Science and the Public Welfare."

23. U.S. Army, *U.S. Army Activity in the U.S. Biological Warfare Programs*, 153, 216.

24. Jeffery K. Smart, "History of Chemical and Biological Warfare: An American Perspective," in Frederick R. Sidell, Ernest T. Takafuji, and David R. Franz (eds.), *Textbook of Military Medicine, Part I: Warfare, Weaponry, and the Casualty: Medical Aspects of Chemical and Biological Warfare* (Washington, DC: Borden Institute, 1997): 1–78; "Interview—Mr. William Patrick"; former Fort Detrick chief of public affairs Norman Covert, former Safety Section chief Manuel Barbeito, and former pilot plant manager Orley Bourland, presentations at "Panel Discussion with Former U.S. Bioweapons Scientists," George Mason University, Fairfax, VA, March 17, 2009; other advances are listed in Clendenin, "Science and Technology at Fort Detrick," 22–23; Rexmond C. Cochrane, *History of the Chemical Warfare Service in World War II (1 July 1940–15 August 1945)*, vol. 2, *Biological Warfare Research in the United States*, U.S. Army Chemical Corps, Historical Section, November 1947, 532–35.

25. Interviews with former U.S. bioweapons scientists between 2008 and 2010. See also Covert, *Cutting Edge*, chaps. 4 and 6; "Fort Detrick Information Book," Fort Detrick, Frederick, MD, 1966 (a copy of the document was given to the author by William Patrick, Frederick, MD, March 18, 2008); Morton Reitman and A. G. Wedum, "Microbiological Safety: Fort Detrick Study Evaluates Relative Infectious Hazards of Microbiological Laboratory Techniques," *Public Health Reports*, vol. 71, no. 7 (July 1956): 659–65; Norman M. Covert, "Scientist's Work Lives on After His Death," *Fort Detrick Standard*, May 29, 1987, 8.

26. U.S. Army, *U.S. Army Activity in the U.S. Biological Warfare Programs*, 153, 216; Manuel Barbeito, former Fort Detrick Safety Section chief, presentation at "Panel Discussion with Former U.S. Bioweapons Scientists."

27. The idea of using balloons as a dissemination mechanism was inspired by the Japanese, who developed the technique during WWII but never filled the balloons with bio-agents. Interestingly, balloons were also considered for the delivery of nuclear weapons. See C. E. Buell and D. W. Stoddard, "Feasibility of Weapon Delivery by Free Balloons," Department of Energy, January 11, 1957, https://www.osti.gov/opennet/index.jsp.

28. U.S. Army, *U.S. Army Activity in the U.S. Biological Warfare Programs*; Smart, "History of Chemical and Biological Warfare," 44, 51–52, 60; Bernstein, "America's Biological Warfare Program in the Second World War," 299–303; Stephen Endicott and Edward Hagerman, *The United States and Biological Warfare: Secrets from the Early Cold War and Korea* (Bloomington, IN: Indiana University Press, 1998); Moon, "The US Biological Weapons Program," 23.

29. Endicott and Hagerman, *The United States and Biological Warfare*, 70–71.

30. Ibid.; Moon, "The US Biological Weapons Program," 23; Jonathan Tucker, "A Farewell to Germs"; David E. Hoffman, *The Dead Hand: The Untold Story of the Cold War Arms Race and Its Dangerous Legacy* (New York: Doubleday, 2009), 125; Bernstein, "Origins of the U.S. Biological Warfare Program," 14. A list of technical reports from Dugway proving ground and Fort Detrick indicates that another warhead for the Sergeant rocket was also tested: *Sergeant Biological Warhead, E23*, vol. 1, *Engineering Test, September 1960–July 1963* (Dugway, UT: Dugway Proving Ground, 1963), Report Number: DPGR-383-VOL-1, CBRNIAC Number: CB-045591, November 1, 1963; *Sergeant Biological Warhead E23*, vol. 2, *Mathematical Evaluation of Capabilities* (Dugway, UT: Dugway Proving Ground, 1963), Report Number: DPGR-383-VOL-2, CBRNIAC Number: CB-012378, January 11, 1963; *Development of Biological Warhead, M211 (E23) for Sergeant Guided Missile* (Pittsburgh: University of Pittsburgh, 1965), Report Number: DA-1-B-543603-D-11601, CBRNIAC Number: CB-022146, January 1, 1965, https://www.muckrock.com/foi/united-states-of-america-10/dugway-proving-ground-technical-reports-4890/#713163-morisy-foia-fa-13-0036-dpg_1964.

31. Jemski, "Estimation of the Aerosol Parameters of Variola Virus (Yamada Strain)," "Project WASP Weapons System Handbook for Chemical and Biological Warheads Honest John

Rocket," Report Number: DPG-61-0342 MC-S-99-61, CBRNIAC Number: CB-084391, January 18, 1961, https://www.muckrock.com/foi/united-states-of-america-10/dugway-proving-ground-technical-reports-4890/#713163-morisy-foia-fa-13-0036-dpg_1964.

32. Edward Regis, *The Biology of Doom: The History of America's Secret Germ Warfare Project* (New York: Henry Holt and Company, 1999). For examples of problematic reproducibility of results and methods in the nuclear field, see Peter Louis Galison, *Image and Logic: A Material Culture of Microphysics* (Chicago, University of Chicago Press, 1997), particularly chap. 3: "The Transfer of Knowledge."

33. Brophy and Cochrane, *The Chemical Warfare Service*, 121. "Camp Detrick" is the former name of Fort Detrick.

34. Dr. Riley Housewright, "Presentation to the American Association of School Business Officials" (presented at Thomas Johnson High School, Frederick, MD, December 8, 1967 (ASM Archives, B-II BP folder); [no author], "Peacetime Uses of Results of Research in Biological Warfare" (presented at Anne Arundel Community College, January 3, 1968) (ASM Archives, B-II BP folder); "Information on Fort Detrick" (1970) (ASM Archives, Folder 13-IIBP, file 1); "About Fort Detrick" (n.d.) (ASM Archives, Folder 13-IIBP, file 8.2). Detailed résumés of Fort Detrick's managers can be found in *Fort Detrick Information Book* and "A Look at . . . the Development and Engineering Laboratories at Fort Detrick," Frederick, MD, report issued by Fort Detrick (n.d.) (ASM Archives).

35. Ibid.

36. An ASM 1957 directory lists 173 members at Fort Detrick. ASM Archives, file: 13-IIBP, Folder 8.6.

37. Detailed résumés of Fort Detrick's managers can be found in *Fort Detrick Information Book* and "A Look at . . . the Development and Engineering Laboratories at Fort Detrick," Frederick, Maryland, report issued by Fort Detrick (n.d.); see also: W. Emmett Barkley, "In Celebration of Dr. Arnold G. Wedum's Legacy," *Journal of the American Biological Safety Association*, vol. 1, no. 1 (1996): 6, http://www.absa.org/abj/abj/960101Barkley.pdf; Covert, *Cutting Edge*, chap. 6.

38. U.S. Army, *U.S. Army Activity in the U.S. Biological Warfare Programs*; Endicott and Hagerman, *The United States and Biological Warfare*," 50.

39. "ASM and Biological Warfare: A Brief Chronology," ASM Archives, http://www.asm.org/index.php/choma3/71-membership/archives/8226-asm-and-biological-warfare-a-brief-chronology; Committee on Biological Warfare meeting minutes, Pentagon, May 15, 1951, (ASM Archives, Regional History, folder 7–63.)

40. *Fort Detrick Information Book*.

41. Interviews with former Fort Detrick Crops Division and pilot plant manager, Frederick, Maryland, March 18, 2008, and former Fort Detrick pilot production plant technician, Frederick, Maryland, March 22, 2008; see also, Clendenin, "Science and Technology at Fort Detrick, 1943–1968," Appendix G: U.S. Army Fort Detrick Scientific Disciplines, 61.

42. "A Look at . . . the Development and Engineering Laboratories at Fort Detrick."

43. Interviews with William C. Patrick, former chief of the Product Development Division, Frederick, Maryland, March 18, 2008, and with former pilot plant technician, Richard Delauter, Frederick, Maryland, March 22, 2008; See also Scott Shane, "Buried Secrets of Biowarfare," *Baltimore Sun*, August, 1, 2004, 1A.

44. Interview with former head of the aerobiology directorate at Fort Detrick, Frederick, MD, March 21, 2008; interviews with former Fort Detrick scientists and technicians between 2008 and 2010; Manuel Barbeito, former Fort Detrick Safety Section chief, presentation at "Panel Discussion with Former U.S. Bioweapons Scientists."

45. Fort Detrick former chief of Public Affairs Norman Covert, Fort Detrick former safety section chief Manuel Barbeito, and former pilot plant manager Orley Bourland, presentations at "Panel Discussion with Former U.S. Bioweapons Scientists," George Mason University, Fairfax, VA, March 17, 2009.

46. Ibid. It is important to note that the friendships existing between personnel at Fort Detrick have survived the termination of the program, as the staff—including administrative, scientific, technical, and support personnel—have met at reunions organized every other year at

Fort Detrick. For a brief summary of the 2008 reunion, see "Former Bioweapons Workers Reunite at Fort Detrick," *The Frederick News-Post*, September 7, 2008, http://www.fredericknewspost.com/archive/article_276ff098-1a11-53ec-9204-4f3e892cb001.html?mode=image&photo=0.

47. Interview with former Fort Detrick pilot plant shift supervisor, Frederick, MD, March 22, 2008.

48. Interview with William C. Patrick, former chief of the Product Development Division, Frederick, MD, March 18, 2008.

49. Interview with former Fort Detrick Crops Division and pilot plant manager, Frederick, MD, March 18, 2008,

50. Ibid.

51. Interview with William C. Patrick, former chief of the Product Process Development Division, Frederick, MD, March 18, 2008.

52. Interviews with former bioweapons scientists, March 18, March 21, and August 11, 2008, Frederick, MD.

53. Interview with Joseph Jemski, former chief of the Test Sphere Program, March 18, 2008, Frederick, MD.

54. Interview with former Fort Detrick Crops Division and pilot plant manager, Frederick, MD, March 18, 2008.

55. Interview with former Fort Detrick bioweapons scientist William C. Patrick, Frederick, MD, March 18, 2008.

56. Interview with former Fort Detrick Crops Division and pilot plant manager, Frederick, MD, March 18, 2008

57. Ibid.

58. The Crops Division operated independently within Fort Detrick and had its own test areas. Therefore, the Product Evaluation Division did not test the plant-related agents developed by that division.

59. Interview with a former Fort Detrick microbiologist in the Agent Control Division, Frederick, MD, March 18, 2008.

60. "Dr. Ira Baldwin: Biological Weapons Pioneer," *American History*, June 12, 2006, http://www.historynet.com/dr-ira-baldwin-biological-weapons-pioneer.htm; "Ira Baldwin's Oral History," *The Living Weapon*, http://www.pbs.org/wgbh/americanexperience/features/primary-resources/weapon-baldwin-oral-history/.

61. Dr. Ira L. Baldwin, Fort Detrick Silver Anniversary Luncheon, ASM, New York City, May 2, 1967 (ASM Archives, 1–22, file 13-II AT, Folder 69.)

62. Due to health issues, Phillips could not receive a commission in the army, but he managed to get his medical records modified and get an assignment as a private. See Covert, "Scientist's Work Lives on After his Death."

63. Baldwin, Fort Detrick Silver Anniversary Luncheon.

64. "Dr. Ira Baldwin: Biological Weapons Pioneer"; Ira L. Baldwin, speech given at Fort Detrick Silver Anniversary Luncheon, New York City, May 2, 1967 (ASM Archives, 1–22, File 13-II AT, Folder 69).

65. Regis, *The Biology of Doom*, 78; Covert, *Cutting Edge*, chap. 7. See also "Dr. Ira Baldwin: Biological Weapons Pioneer."

66. Baldwin, Fort Detrick Silver Anniversary Luncheon; "Dr. Ira Baldwin: Biological Weapons Pioneer."

67. Ibid. In 1942, before the Fort Detrick facility was established, the scientific team that designed the U.S. bioweapons program was temporarily based at Edgewood Arsenals.

68. [No author], "Peacetime Uses of Results of Research in Biological Warfare."

69. United States Army, *U.S. Army Activity in the U.S. Biological Weapons Programs*, 30.

70. Ibid.

71. Committee on Biological Warfare meeting minutes, Pentagon, May 15 1951 (ASM Archives, Regional History 7–63 folder).

72. Interview with former head of the aerobiology directorate at Fort Detrick, Frederick, MD, March 20, 2008; interviews with former Fort Detrick scientists and technicians between 2008 and 2010.

73. Interview with former Fort Detrick microbiologist in the Agent Control Division, Frederick, MD, March 18, 2008.

74. Interviews with former US bioweapons scientists from 2008 to 2010.

75. Interviews with former U.S. bioweapons scientists and technicians between 2008 and 2010.

76. Interview with former Fort Detrick microbiologist in the Agent Control Division, Frederick, MD, March 18, 2008

77. Dugway Proving Ground, "Scientific Publication, Fort Detrick 1946–1972," December 1976; "Information on Fort Detrick" (ASM Archives, Folder 13-IIBP); "Selected Contributions of the Biological Laboratories at Fort Detrick to Science and the Public Welfare 1943–1970" (ASM Archives).

78. Cochrane, *History of the Chemical Warfare Service in World War II (1 July 1940–15 August 1945)*, 546; Brophy and Cochrane, *The Chemical Warfare Service: From Laboratory to Field*, 120; see also Julian Robinson Perry and Milton Leitenberg, *The Problem of Chemical and Biological Warfare*, vol. 1 (Stockholm: SIPRI, 1971), footnotes 46, 121.

79. American Society for Microbiology, http://journals.asm.org/.

80. Cochrane, *History of the Chemical Warfare Service in World War II (1 July 1940–15 August 1945)*, 545. It is worth noting that a 1963 overview of Fort Detrick's activities indicates that an average of one patent a month was issued or submitted. The document has no author, but it was likely issued by the Army. The document does not specify whether the patent average concerns only 1963 or covers Fort Detrick's activities since 1942. See "Why Fort Detrick: An Integrated R&D Report," August 12, 1963 (ASM Archives).

81. Interview with former chief of the Applied Aerobiology Division, Frederick, MD, March 21, 2008.

82. Ibid.

83. Interview with former Fort Detrick Crops Division and pilot plant manager, Frederick, MD, March 18, 2008.

84. Interview with former Fort Detrick microbiologist in the Agent Control Division, Frederick, MD, March 18, 2008.

85. Interview with William C. Patrick, Frederick, MD, March 18, 2008.

86. Interview with former Fort Detrick Crops Division and pilot plant manager, Frederick, MD, March 18, 2008.

87. Ibid.

88. Interview with Joseph Jemski, Frederick, MD, March 18, 2008.

89. American Society for Microbiology, http://journals.asm.org/.

90. These features were particularly important within the pilot plants, which operated around the clock. For example, shift workers in the bacterial pilot plant at Fort Detrick invariably worked with the same colleagues, most of whom served at Fort Detrick since the early to mid-1940s and until the official U.S. declaration of the end of the bioweapons program in 1969. Another unique characteristic of the pilot plant was that all of its shift workers were interchangeable, such that one operator was trained to do the work of another one. Fort Detrick instituted this policy to ensure continuity of the production process around the clock, independent of rest breaks or personal leave.

Interviews with former pilot plant shift supervisor, Joseph Jemski, and William C. Patrick, Frederick, MD, March 22, March 18, and June 13, 2008, respectively.

91. Guillemin, *Biological Weapons*, 101–6; Moon, "The US Biological Weapons Program," 9–46; Wright, "Evolution of the Biological Warfare Policy: 1945–1990"; Bernstein, "Origins of the U.S. Biological Warfare Program"; Endicott and Hagerman, *The United States and Biological Warfare.*

92. Bernstein, "Origins of the U.S. Biological Warfare Program," 1–14; see also Wright, "Evolution of the Biological Warfare Policy: 1945–1990."

93. Bernstein, "Origins of the U.S. Biological Warfare Program," 11.

94. Ibid.

95. U.S. Army, *U.S. Army Activity in the U.S. Biological Warfare Programs*, 45–48; see also "The Department of Defense's Inquiry into Project 112/Shipboard Hazard and Defense (SHAD) tests."

96. Bernstein, "Origins of the U.S. Biological Warfare Program"; Endicott and Hagerman, *The United States and Biological Warfare.*

97. U.S. Army, *U.S. Army Activity in the U.S. Biological Warfare Programs*.

98. Endicott and Hagerman, *The United States and Biological Warfare*, 65; Moon, "The US Biological Weapons Program."

99. Clendenin, "Science and Technology at Fort Detrick"; *Report by the Committee on Biological Warfare*, Department of Defense Research and Development Board, Washington, DC, January 24, 1950, 9 (ASM Archives); Endicott and Hagerman, *The United States and Biological Warfare*, 48. See also Wright, "Evolution of the Biological Warfare Policy: 1945–1990," 33.

100. Endicott and Hagerman, *The United States and Biological Warfare*, 48.

101. Clendenin, "Science and Technology at Fort Detrick"; *Report by the Committee on Biological Warfare*, January 24, 1950, 9 (ASM Archives); Endicott and Hagerman, *The United States and Biological Warfare*, 48. See also Wright, "Evolution of the Biological Warfare Policy: 1945–1990," 33.

102. Endicott and Hagerman, *The United States and Biological Warfare*, ix, 83–84; Moon, "The US Biological Weapons Program," 23.

103. Endicott and Hagerman, *The United States and Biological Warfare*, 87.

104. U.S. Army, *U.S. Army Activity in the U.S. Biological Warfare Programs*.

105. Ibid., 41–48.

106. Chemical herbicide studies were conducted at Fort Detrick and supported by the Air Force, which started spraying them in Vietnam in 1963. The study of incapacitating agents—such as staphylococcal toxins, Q fever, and Venezuelan equine encephalitis—were also conducted at Fort Detrick, although there is no indication that they were considered for use in Vietnam. See Endicott and Hagerman, *The United States and Biological Warfare*.

107. "Why Fort Detrick: An Integrated R&D Report," August 12, 1963 (ASM Archives, File 13 IIBP, Folder 8.2).

108. U.S. Army, *U.S. Army Activity in the U.S. Biological Warfare Programs*, 50–51.

109. Management of the nuclear weapons program was transferred from the Manhattan Engineer District to the Atomic Energy Commission in 1947, then to the Nuclear Regulatory Commission in 1974, and eventually to the Department of Energy in 1977 (United States Department of Energy, *Historical Resources*, http://energy.gov/management/history/historical-resources); see also U.S. Department of Energy, *The Manhattan Project: Making the Atomic Bomb*, National Security History Series (Washington, DC: Department of Energy, 2010), http://energy.gov/sites/prod/files/Manhattan_Project_2010.pdf.

110. Moon, "The US Biological Weapons Program"; Guillemin, *Biological Weapons*, chaps. 3, 4; U.S. Army, *U.S. Army Activity in the U.S. Biological Warfare Programs*.

111. Bernstein, "Origins of the U.S. Biological Warfare Program," 12.

112. U.S. Army, *U.S. Army Activity in the U.S. Biological Warfare Programs*.

113. Ibid., 30–38.

114. Ibid.

115. Ibid.

116. Ira L. Baldwin, speech given at Fort Detrick Silver Anniversary Luncheon.

117. Ibid., 21; Covert, *Cutting Edge*, appendix: Fort Detrick Commanders.

118. Bernstein, "Origins of the U.S. Biological Warfare Program," 19–20.

119. Endicott and Hagerman, *The United States and Biological Warfare*, 70–72, 84–86.

120. Guillemin, *Biological Weapons*, 101–6; see also Moon, "The US Biological Weapons Program."

121. Smart, "History of Chemical and Biological Warfare," 51, 60; U.S. Army, *U.S. Army Activity in the U.S. Biological Warfare Programs*. The Navy was also very much involved in the bioweapons program, but most of its work centered on Navy needs. The Navy provided almost one-quarter of the technical staff at Fort Detrick and related tests sites. The Navy also had a separate research unit at the University of California. Endicott and Hagerman, *The United States and Biological Warfare*, 73–74; Brophy and Cochrane, *The Chemical Warfare Service*, 109–10.

122. Guillemin, *Biological Weapons*, 109.

123. Endicott and Hagerman, *The United States and Biological Warfare*, 86.

124. *Report by the Committee on Biological Warfare*, , January 10, 1950, ASM Archives, 11.

125. Smart, "History of Chemical and Biological Warfare," 55.

126. Interview with former Fort Detrick pilot plant shift supervisor, Frederick, MD, March 22, 2008.

127. Interview with Richard Delauter, Frederick, MD, August 12, 2008.

128. Ibid.

129. Interview with William C. Patrick, March 18, 2008, Frederick, MD.

130. See Moon, "The US Biological Weapons Program"; Ira L. Baldwin, speech given at Fort Detrick Silver Anniversary Luncheon, New York City, May 2, 1967; *Report by the Committee on Biological Warfare*, January 10, 1950, 1–22; *Report by the Committee on Biological Warfare*, January 24, 1950, 9; "Why Fort Detrick: An Integrated R&D Report"; Martin, Christopher, and Eitzen, "History of Biological Weapons."

131. *Report by the Committee on Biological Warfare*, January 10, 1950, 10–11.

132. "Dr. Ira Baldwin: Biological Weapons Pioneer."

133. Clendenin, "Science and Technology at Fort Detrick 1943–1968"; U.S. Army, *U.S. Army Activity in the U.S. Biological Warfare Programs*; Endicott and Hagerman, *The United States and Biological Warfare*, 32, 35; Smart, "History of Chemical and Biological Warfare"; Christopher, Cieslak, Pavlin, and Eitzen, "Biological Warfare."

134. *Report by the Committee on Biological Warfare*, January 10, 1950, 14.

135. Ibid.; Smart, "History of Chemical and Biological Warfare"; U.S. Army, *U.S. Army Activity in the U.S. Biological Warfare Programs*.

136. "Confidential Memorandum for Dr. Colin MacLeod to Be Used at His Discretion," 1962 (ASM Archives, File: 13-IIBP, folder F.F).

137. Interview with William Patrick, Frederick, MD, March 18, 2008.

138. Lilian Hoddeson, Paul W. Henriksen, Roger A. Meade, and Catherine Westfall, *Critical Assembly: A Technical History of Los Alamos during the Oppenheimer Years* (Cambridge: Cambridge University Press, 1993).

139. See, for example, Joby Warrick, "As Syria Deteriorates, Neighbors Fear Bioweapons Threat," *Washington Post*, September 4, 2013, http://www.washingtonpost.com/world/national-security/as-syria-deteriorates-neighbors-fear-bioweapons-threat/2013/09/04/ed5b47e0-10ad-11e3-85b6-d27422650fd5_print.html; Commission on the Prevention of WMD Proliferation and Terrorism, *World at Risk* (New York: Vintage, 2008). For a critique of such assessments, see Milton Leitenberg, *Assessing the Biological Weapons and Bioterrorism Threat* (Carlisle, PA: U.S. Army Strategic Studies Institute, 2005).

Chapter 5

1. Sonia Ben Ouagrham and Kathleen M. Vogel, *Conversion at Stepnogorsk: What the Future Holds for Former Bioweapons Facilities*, Occasional Paper no. 28 (Ithaca, NY: Cornell University Peace Studies Program, February 2003), http://pacs.einaudi.cornell.edu/system/files/Stepnogorsk-28.pdf.

2. Due to extreme secrecy and the disintegration of the bioweapons program after the breakup of the Soviet Union, there is no publicly accessible official archive of Soviet bioweapons developments, and no exact inventory of program facilities, personnel, and stockpiles. However, an insightful degree of transparency arose based on interviews with defectors and research conducted after the breakup. For example, see Milton Leitenberg and Raymond A. Zilinskas, *The Soviet Biological Weapons Program: A History* (Cambridge, MA: Harvard University Press, 2012); Ken Alibek and Stephen Handelman, *Biohazard: The Chilling True Story of the Largest Covert Biological Weapons Program in the World, Told from the Inside by the Man Who Ran It* (New York: Random House, 1999); Igor Domaraskij and Wendy Orent, *Biowarrior: Inside the Soviet/Russian Biological War Machine* (Amherst, NY: Prometheus Books, 2003); Sonia Ben Ouagrham-Gormley and Kathleen M. Vogel, "The Social Context Shaping Bioweapons (Non) proliferation," *Biosecurity and Bioterrorism: Biodefense Strategy, Practice, and Science*, vol. 8, no. 1

(March 2010): 9–24; Sergei Popov and Marina Voronova, "Russian Bioweapons: Still the Best-Kept Secret?" *Nonproliferation Review* (Fall 2004): 1–14; Ben Ouagrham and Vogel, *Conversion at Stepnogorsk*.

3. Sources differ on the number of facilities composing the bioweapons program before the war. Some sources take into account only military institutes studying human diseases, while others also include institutes studying animal diseases. See Leitenberg and Zilinskas, *The Soviet Biological Weapons Program*, 22; and Valentin Bojtzov and Erhard Geissler, "Military Biology in the USSR, 1920–45," in Erhard Geissler and John Ellis van Courtland Moon (eds.), *Biological and Toxin Weapons: Research, Development and Use from the Middle Ages to 1945* (Oxford: Oxford University Press, 1999), 157.

4. On the anti-plague system, see Alexander Melikishvili, "Genesis of the Anti-Plague System: The Tsarist Period," *Critical Reviews in Microbiology*, vol. 32, no. 1 (2006): 19–31; Sonia Ben Ouagrham-Gormley, "Growth of the Anti-Plague System during the Soviet Period," *Critical Reviews in Microbiology*, vol. 32, no. 1 (2006): 33–46; Raymond Zilinskas, "The Anti-Plague System and the Soviet Biological Warfare Program," *Critical Reviews in Microbiology*, vol. 32, no. 1 (2006): 47–64.

5. Ben Ouagrham-Gormley and Vogel, "The Social Context Shaping Bioweapons (Non) proliferation"; Ben Ouagrham-Gormley, "Growth of the Anti-Plague System during the Soviet Period."

6. Ben Ouagrham and Vogel, *Conversion at Stepnogorsk*.

7. Soviet scientists called their lab outfit "pajamas."

8. U.S. General Accounting Office, *Biological Weapons: Effort to Reduce Former Soviet Threat Offers Benefits, Poses New Risks*, *GAO-NSIAD-00-138* (Washington, DC: U.S. General Accounting Office, 2000), 10.

9. Interview with Ken Alibek, former deputy director of Biopreparat, Manassas, VA, August 2001.

10. Sonia Ben Ouagrham, "Biological Weapons Threats from the Soviet Union" (working paper, Series on the Former Soviet States, Liechtenstein Institute on Self-Determination, Princeton University, 2003), http://www.princeton.edu/lisd/publications/wp_russiaseries_ouagrham.pdf.

11. Alibek and Handelman, *Biohazard*, 43.

12. The budget announced by Gorbachev was 77.3 billion rubles. With an exchange rate of $1 = 0.6R prevailing at the time, the military budget in dollars was $46 billion. When in 1971 the exchange rate was $1 = 0.9R, some analysts suggested that using an exchange rate of $1 = 0.5R would take into account the greater buying power of the ruble (due to the lower costs of labor, for example) and provide a more accurate conversion of Soviet expenditures into dollars. See Mose L. Harvey, Leon Goure, and Vladimir Prokofieff, *Science and Technology as an Instrument of Soviet Policy* (Coral Gables, FL: Monographs in International Affairs, Center for Advanced International Studies: University of Miami, 1972), 72–73; "Russian Military Budget," GlobalSecurity.org, http://www.globalsecurity.org/military/world/russia/mo-budget.htm; "Exchange Rate Cut for Ruble," *New York Times*, November 4, 1991, http://www.nytimes.com/1991/11/04/world/exchange-rate-cut-for-ruble.html.

13. Leitenberg and Zilinskas, *The Soviet Biological Weapons Program*, 45, 702; Jonathan B. Tucker, *Scourge: The Once and Future Threat of Smallpox* (New York: Atlantic Monthly Press, 2001), chap. 8; Ken Alibek, "Behind the Mask: Biological Warfare," *Perspective*, vol. 9, no. 1 (September–October 1998).

14. In the 1940s, the Kirov institute was named Sanitary-Technology Institute (STI). Its name later changed to Scientific Research Institute of Epidemiology and Hygiene.

15. Leitenberg and Zilinskas, *The Soviet Biological Weapons Program*, 29. It is not clear whether Soviet scientists developed this method endogenously, or if they had access to data from the American program.

16. Igor V. Domaradskij and Wendy Orent, "Achievements of the Soviet Biological Weapons Programme and Implications for the Future," *Revue Scientifique et Technique (International Office of Epizootics)*, vol. 25, no. 1 (2006): 155.

17. Genetic engineering emerged after the United States gave up its program in 1969; Ken Alibek, "Behind the Mask"; Jonathan Tucker, "Bioweapons from Russia: Stemming the Flow," *Issues in Science and Technology* (Spring 1999), http://www.issues.org/15.3/p_tucker.htm.

18. Leitenberg and Zilinskas, *The Soviet Biological Weapons Program*, 703.

19. Sergei Popov, "Inside the Soviet Bioweapon Machine: Igor Domardskij's *Biowarrior*," *Nonproliferation Review*, vol. 11, no. 2 (Summer 2004): 200–205; Interview—Serguei Popov, *Journal of Homeland Security* (November 13, 2000), http://www.judiciary.senate.gov/hearings/testimony.cfm?id=4f1e0899533f7680e78d03281fff2b71&wit_id=4f1e0899533f7680e78d03281fff2b71-0-5; Domaradskij and Orent, "Achievements of the Soviet Biological Weapons Programme."

20. Leitenberg and Zilinskas, *The Soviet Biological Weapons Program*, 703; Domaradskij and Orent, "Achievements of the Soviet Biological Weapons Programme," 157.

21. Jonathan B. Tucker, *Scourge*, chap. 8; Sergei Popov, former department head and project manager at Vector and Obolensk (presentation at "Panel Discussion with U.S. and Russian Former Bioweapons Scientists," George Mason University, Fairfax, VA, March 29, 2010).

22. Domaradskij and Orent, "Achievements of the Soviet Biological Weapons Programme," 158–59.

23. Ben Ouagrham and Vogel, *Conversion at Stepnogorsk*, 21.

24. Leitenberg and Zilinskas, *The Soviet Biological Weapons Program*, 703–704, Conclusion.

25. Ibid., 313–21.

26. Dennis M. Gormley, "Hedging Against the Cruise-Missile Threat," *Survival*, vol. 40, no. 1 (Spring 1998): 95–96.

27. One caveat is that there is very little information about some of the research and weaponization work done at MOD facilities. So it is conceivable that more was achieved at these facilities.

28. Bojtzov and Geissler, "Military Biology in the USSR, 1920–45." See also Domaradskij and Orent, *Biowarrior*, 134.

29. Bojtzov and Geissler, "Military Biology in the USSR, 1920–45"; Leitenberg and Zilinskas, *The Soviet Biological Weapons Program*, 18–19.

30. Ibid.

31. Ken Alibek, "Behind the Mask: Biological Warfare," *Perspective*, vol. 9, no. 1 (September–October 1998), http://www.bu.edu/iscip/vol9/Alibek.html; Sheldon Harris, "Japanese Biological Warfare Experiments and Other Atrocities in Manchuria, 1932–1945, and the Subsequent United States Cover Up: A Preliminary Assessment," *Crime, Law and Social Change*, vol. 15, no. 3, (1991): 171–99; Alibek and Handelman, *Biohazard*, 37.

32. Alibek and Handelman, *Biohazard*; interviews with former Soviet bioweapons scientists, 2006–2012.

33. It is important to note that the scattered and compartmentalized character of the Soviet bioweapons program was strongly reinforced in the 1970s, when the program became illegal, but it was a feature of the program from its inception in the 1920s. See Bojtzov and Geissler, "Military Biology in the USSR, 1920–45."

34. Interview with a former Soviet bioweapons scientist, Obolensk, Russia, July 9, 2008.

35. Ben Ouagrham-Gormley and Vogel, "The Social Context Shaping Bioweapons (Non) proliferation."

36. Leitenberg and Zilinskas, *The Soviet Biological Weapons Program*, 219.

37. Interview with former Soviet bioweapons scientists, Almaty, Kazakhstan, August 13, 2008.

38. Interview with Sergei Popov, Manassas, VA, August 17, 2006.

39. Interview with a former Soviet bioweapons scientist, Obolensk, Russia, July 9, 2008.

40. Domaradskij and Orent, *Biowarrior*, 203.

41. Interview with former Soviet bioweapons scientists, Almaty, Kazakhstan, August 13, 2008.

42. Ibid.

43. Ibid.

44. Interview with Sergei Popov, Manassas, VA, July 19, 2006. Also, Sergei Popov, former department head and project manager at Vector and Obolensk (presentation at "Panel Discus-

sion with U.S. and Russian Former Bioweapons Scientists," George Mason University, Fairfax, VA, March 29, 2010).

45. Popov, "Inside the Soviet Bioweapon Machine"; Domaradskij and Orent, "Achievements of the Soviet Biological Weapons Programme."

46. Domardskij and Orent, *Biowarrior*, chap. 11.

47. Interview with Sergei Popov, Manassas, VA, March 17, 2008.

48. Ibid.

49. Ibid.

50. Ibid. Interview with former Soviet bioweapons scientists, Manassas, VA, April 9, 2008.

51. Interview with Sergei Popov, Manassas, VA, March 17, 2008.

52. Kathleen Vogel, *Analyzing Knowledge Production in Soviet Bioweapons Development: A New Approach for Assessing Brain Drain Proliferation Threats* (Washington, DC: National Council for Eurasian and East European Research, 2003), 34, http://www.ucis.pitt.edu/nceeer/2003_817_18_Vogel.pdf.

53. Interview with a former Soviet bioweapons scientist, Rosslyn, VA, August 19, 2011.

54. Interview with former bioweapons scientists, Moscow, Russia, May 27, 2008.

55. Interview with former bioweapons scientists, Moscow, Russia, June 11 and September 2, 2008, and Sergei Popov, Manassas, VA, July 19, 2006.

56. Interview Sergei Popov, Manassas, VA, July 19, 2006.

57. Ibid.

58. Ibid. Interview with a former bioweapons scientist, Moscow, Russia, June 11, 2008.

59. Interview with Sergei Popov, Manassas, VA, July 19, 2006.

60. In his memoir, Igor Domaradskij suggests that the Institute for Ultra-Pure Preparation at St. Petersburg had a similar work environment as Vector. See Domaraskij and Orent, *Biowarrior*, 246.

61. Interviews with former Soviet bioweapons scientists between 2006 and 2011. It is important to note that this privileged position, which began under Stalin, applied to all personnel working in the defense sector. Early retirements were especially applicable to personnel working with nuclear, biological, or chemical weapons due to the anticipated hazards involved with such work.

62. Lev. A. Fedorov, *Sovietskoe Biologicheskoe Opuzhie: Istoria, Ekologia, Politika* [Soviet biological weapons: History, ecology, politics] (Moscow: Union of Chemical Safety, 2005), http://www.seu.ru/cci/lib/books/bioweapon/.

63. Some of the scientists who were sent as prisoner-laborers to bioweapons facilities continued working at these locations after their release. Domaraskij and Orent, *Biowarrior*, chap. 3; Vladimir J. Birstein, *The Perversion of Knowledge: The True Story of Soviet Science* (Cambridge, MA: Westview Press, 2001), 123, chap. 4.

64. Piotr Burgasov served under Lavrenty Beria between 1950 and 1953. He later worked on anthrax at the Sverdlovsk Institute, until his appointment as deputy minister of health in 1965, a position he kept until 1986. Evgeniya Kvitko, "Ospa—Tozhe nieplokhoe oruzhie" [Smallpox—it is not a bad weapon], interview with General Burgasov, *Moscow News*, 2001, available at http://kungrad.com/aral/island/ospa/.

65. Loren R. Graham, *Science and Philosophy in the Soviet Union* (New York: Alfred A. Knopf, 1972), chap. 6.

66. Birstein, *The Perversion of Knowledge*, 45–50, chap. 4; David Holloway, *Stalin and the Bomb: The Soviet Union and Atomic Energy, 1939–1956* (New Haven: Yale University Press, 1994), chap. 7.

67. Domaradskij and Orent, "Achievements of the Soviet Biological Weapons Programme"; see also Domaradskij and Orent, *Biowarrior*, 134; Harvey, Goure, and Prokofieff, *Science and Technology as an Instrument of Soviet Policy*, 48–49.

68. Graham, *Science and Philosophy in the Soviet Union*, chap. 6.

69. Interview with a former Soviet bioweapons scientist, Manassas, VA, April 9, 2008.

70. For example, Sergei Popov was not promoted beyond the position of department head because he was not a member of the Communist Party. Sergei Popov, former department head and project manager at Vector and Obolensk (presentation at "Panel Discussion with U.S. and

Russian Former Bioweapons Scientists," George Mason University, Fairfax, VA, March 29, 2010).

71. Interview with a former Soviet bioweapons scientist, Obolensk, Russia, July 9, 2008.
72. Ibid.
73. Domardskij and Orent, *Biowarrior*, 102.
74. Domaradskij and Orent, "Achievements of the Soviet Biological Weapons Programme," 154–56; Sergei Popov, "Inside the Soviet Bioweapon Machine."
75. Interviews with former bioweapons scientists, Moscow, Russia, June 3 and 11, 2008.
76. Ibid. Interview with Sergei Popov, Manassas, VA, July 19, 2006.
77. Ibid.
78. Interview with a former bioweapons scientist, Moscow, Russia, June 11, 2008; Domaradskij and Orent, "Achievements of the Soviet Biological Weapons Programme," 156.
79. Ben Ouagrham-Gormley and Vogel, "The Social Context Shaping Bioweapons (Non) proliferation."
80. Sonia Ben Ouagrham, "The Specifics of Soviet Defense Enterprises," in Vlad E. Genin (ed.), *The Anatomy of Russian Conversion* (Stanford, CA: Vega Press, 2001).
81. Interview with Sergei Popov, Manassas, VA, March 17, 2008.
82. Ibid.
83. Thane Gustafson, "Why Doesn't Soviet Science Do Better Than It Does?" in Linda L. Lubrano and Susan Gross Solomon (eds.), *The Social Context of Soviet Science* (Boulder, CO: Westview, 1980), 45; Peter Keen, *Soviet Scientists and the State* (Albany: State University of New York Press, 1984), 58.
84. Interview with a former Soviet bioweapons scientist, Obolensk, Russia, July 9, 2008.
85. Interview with Sergei Popov, Manassas, VA, March 17, 2008.
86. Sergei Popov, former department head and project manager at Vector and Obolensk (presentation at "Panel Discussion with U.S. and Russian Former Bioweapons Scientists," George Mason University, Fairfax, VA, March 29, 2010).
87. Interview with Sergei Popov, Manassas, VA, March 17, 2008.
88. Ibid.
89. Ibid.; Sergei Popov, former department head and project manager at Vector and Obolensk (presentation at "Panel Discussion with U.S. and Russian Former Bioweapons Scientists," George Mason University, Fairfax, VA, March 29, 2010).
90. Ibid.
91. Interview with a former bioweapons scientist, Moscow, Russia, June 11, 2008.
92. Interview with Sergei Popov, Manassas, VA, July 19, 2009.
93. Ibid.

Chapter 6

1. UNMOVIC, *Compendium of Iraq's Proscribed Weapons Programmes in the Chemical, Biological and Missile Areas*, United Nations, June 2007, http://www.un.org/depts/unmovic/new/pages/compendium.asp.
2. Ibid.
3. Ibid., 836.
4. Ibid., 918–19.
5. Ibid., 785, 837–59, 895–96; Iraq Survey Group, *Comprehensive Report of the Special Advisor to the DCI on Iraq's WMD*, vol. 3, Central Intelligence Agency, September 30, 2004, https://www.cia.gov/library/reports/general-reports-1/iraq_wmd_2004/chap6.html.
6. Ibid., 772.
7. Ibid.
8. Ibid., vol. 5.
9. E-mail communications with Rod Barton, member of the Iraq Survey Group, and Milton Leitenberg, University of Maryland, January 29, 2013; see also UNMOVIC, *Compendium of Iraq's Proscribed Weapons Programmes*, 788, 1055.

10. E-mail communication with Rod Barton, February 1, 2013.

11. Rajeev Syal, "MP's Cloak and Dagger Mission: Ask Dr. Germ about Iraq's Weapons," *Times*, March 14, 2006, 4.

12. Christopher Dickey and Colin Soloway, "The Secrets of Dr. Germ," *Newsweek*, vol. 140, no. 24 (December 9, 2002): 40–43.

13. Rod Barton, *The Weapons Detective: The Inside Story of Australia's Top Weapons Inspector* (Melbourne: Black Inc. Agenda, 2006), 131.

14. Melinda Liu, "What 'Mrs. Anthrax' Told Me," *Newsweek*, December 21, 2005, http://www.thedailybeast.com/newsweek/2005/12/21/what-mrs-anthrax-told-me.html; "Iraq's Women Scientists," *BBC News*, September 22, 2004, http://news.bbc.co.uk/2/hi/middle_east/3679040.stm.

15. Barton, *The Weapons Detective*, 170.

16. E-mail communication with Rod Barton, member of the Iraq Survey Group, February 1, 2013.

17. Ibid.

18. UNMOVIC, *Compendium of Iraq's Proscribed Weapons Programmes*, 778–79, 821–35.

19. The reasons for Hindawi's departure are not well established. Press reports indicate that he was fired after a dispute with Iraqi senior officials over financial irregularities in the program. It is also possible that he preferred working in an academic environment and had only planned to help start the program in view of winning the war against Iran. E-mail communication with Rod Barton, February 1, 2013; Judith Miller, "Baghdad Arrests a Germ Specialist," *New York Times*, March 24, 1998, http://www.nytimes.com/1998/03/24/world/baghdad-arrests-a-germ-specialist.html?src=pm.

20. Iraq Survey Group, *Comprehensive Report of the Special Advisor*, vol. 3, 19, 42.

21. UNMOVIC, *Compendium of Iraq's Proscribed Weapons Programmes*, 774, 788, 837.

22. E-mail communications with Rod Barton, February 1, 10, and 11, 2013; Iraq Survey Group, *Comprehensive Report of the Special Advisor.*

23. E-mail communication with Rod Barton, February 11, 2013.

24. Ala Bashir and Lars Sigurd Sunnanå, *The Insider: Trapped in Saddam's Brutal Regime* (London: Abacus, 2005), 210–13; see also Iraq Survey Group, *Addendums to the Comprehensive Report of the Special Advisor to the DIC on Iraq's WMD*, Central Intelligence Agency, March 2005, 39–42

25. Iraq Survey Group, *Comprehensive Report of the Special Advisor*, vol. 1, 12; vol. 3, 86; Kevin Woods, James Lacey and Williamson Murray, "Saddam's Delusions: The View from the Inside," *Foreign Affairs*, vol. 85, no. 3 (May/June, 2006): 2–26.

26. E-mail communication with Rod Barton, February 1, 2013.

27. Iraq Survey Group, *Comprehensive Report of the Special Advisor*, vol. 1; *Addendums to the Comprehensive Report of the Special Advisor*.

28. Ibid., vol. 3, 19.

29. Bashir and Sunnanå. *The Insider*, 275–76.

30. UNMOVIC, *Compendium of Iraq's Proscribed Weapons Programmes*, 790; Iraq Survey Group, *Comprehensive Report of the Special Advisor*, vol. 3, 8–11, 48.

31. Chandré Gould and Peter Folb, *Project Coast: Apartheid's Chemical and Biological Weapons Program* (Geneva: United Nations Institute for Disarmament Research, 2002); Stephen Burgess and Helen Purkitt, "The Secret Program: South Africa's Chemical and Biological Weapons," http://cpc.au.af.mil/PDF/book/thewarnexttimechapter3.pdf.

32. Gould and Folb indicate that RRL received an estimated total budget of about R99 million (about $27 million at 1995's exchange rate [$1 = R3.66]). Additional work was conducted by private companies, which received an additional R20 million or so (about $5.5 million) for their services. Burgess and Purkitt indicate that Project Coast received a budget of $10 million per year, which probably funded both chemical and biological weapons activities. See Gould and Folb, *Project Coast*, 100–14; Burgess and Purkitt, "The Secret Program," 32.

33. Daan Goosen's testimony before the Truth and Reconciliation Commission, Cape Town, South Africa, June 11, 1998, quoted in Chandré Gould and Peter Folb, "The Role of Professionals in the South African Biological and Chemical Warfare Programme," *Minerva*, vol. 40, no. 1 (2002): 83.

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